SPECIAL ASPECTS OF CYCLOTRON RF SYSTEMS

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Abstract

Modern cyclotron rf systems benefit greatly from the technical developments in the allied fields of high power military and commercial transmitters. Special stability requirements and high Qs still require a special art in cyclotrons which is not exhibited in other systems. A survey of the problems and their solutions is given with some examples from current practise.

The basic principles of design of cyclotron rf systems that are used to provide the energy to the circulating ions have changed little since the concept was developed by E. O. Lawrence in 1930. The only development that caused a major change in design philosophy was the idea of phase focussing and frequency modulation. Present rf systems therefore group themselves into two different categories, the fixed frequency machines which are now practically all of the sector focussed variety and the fm machines of which the improved MSC at CERN[1]) is the foremost example.

With increasing energies and increasing beam currents the main demand on the rf designer has been one of increasing power input and various techniques have been evolved to deliver the large powers now demanded. The TRIUMF cyclotron[2]) has an rf system capable of delivering 1.8 Mwatt of power.

Along with these increases in power have come demands from the beam designers for ever increasing voltage and frequency stability or reproducibility in the case of synchro-cyclotrons and the increasing beam currents have demanded wave shape tailoring or modification to increase extraction efficiencies to the level at which a machine can be operated without the tank and resonators becoming so radioactive that the only method of repair amounts to a complete demolition of an existing system and a replacement by a new piece of hardware, a lengthy and undesired procedure.

The higher power levels have had their attendant problems of resonator cooling and the easy tuning techniques of the early machines have been replaced by elaborate schemes of various kinds. One of the most ingenious of these is the cavity bending technique employed in the SIN accelerator[3]).

Resonators

Since the purpose of the rf system is to deliver the accelerating fields to the particles and the fields are developed in the resonators, let us briefly consider the problems faced by the resonator designer.

The resonator is basically an rf cavity which in its simplest form is a $\frac{1}{4}\lambda$ resonant structure which can be thought of as a shorted transmission line which has been distorted by a lateral stretching. The currents induced by the rf field flow only along the metal surfaces. The inner conductor has been hollowed out for the passage of the accelerated particles. This basic design is now modified by varying the line impedance by dimensional changes or by replacement of the line itself by lumped constant elements. This hybrid structure will now resonate at somewhat lower Q than the simple cavity system but has the advantage that it can be tuned at various rates and in various places by means of the lumped constant elements. The variable impedances can be used to tailor the voltage distribution and this distribution can thus be adjusted to give the required high voltage at the acceleration gap and keep the voltage stresses at the feedthrough insulators and mounting structures acceptably low (Fig. 1).

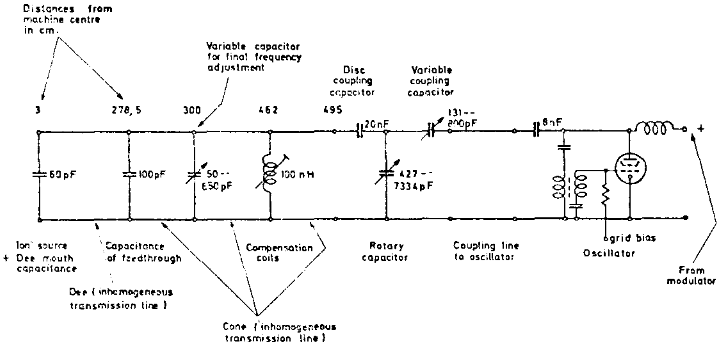

Fig. 1 : Lumped constant equivalent circuit with the voltage distribution for the CERN synchro-cyclotron

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The basic cyclotron frequency for hydrogen ions sets the primary cavity length of a few meters and harmonic acceleration is used with increasing ionic mass. The structure must therefore be rigid enough to keep its geometry, must be cooled to carry away the skin current heating and must be clean enough not to affect the vacuum in the tank. To keep the Q high and hence the power low the surface to volume ratio should be as low as possible. The limitation of the current to the metal surfaces demands good surface conductivity in the top few mils of metal and the way this is normally done is to plate the cavity with a good conductor such as copper or silver. The cost of silver is prohibitive and therefore copper is normally used to line structures or to plate surfaces. The technique of roll bonding copper to aluminum with the inclusion of water channels into the metal stack by means of masking and deposition of a separation layer which is subsequently inflated (Fig. 2) has become the accepted way of producing a light, well cooled resonator skin. The welding of water connections to such plates has produced some initial problems but modern heliarc or argonarc welding procedures seem to give reliable joints. It is interesting to note that highly polished aluminum surfaces give resonator Q's only about 10% less than copper plated surfaces and the extra problems associated with such platings may not be necessary in most machines operating at moderate power levels. The large SIN cavities are of aluminum.

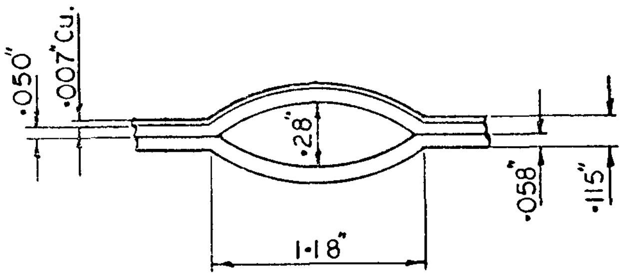

Fig. 2 : A section of roll bonded resonator structure consisting of a surface copper layer and two layers of aluminum

Clean vacuum systems permit voltage gradients between 50 kV/cm and 100 kV/cm on the rf electrodes which allows much higher voltages to be achieved in the accelerating gaps. The 500 kV on the SIN resonators is a good example of what can be achieved in oil free vacuum conditions.

Insulators have been commonly avoided due to the unfortunate experiences of most cyclotron systems using insulators in the early days, in which breakdown of the insulator surfaces after a short period of operation led to frequent shutdowns. Improved vacuum techniques have helped in this regard and the Columbia cyclotron has gone as far as to even support magnet shims in the rf structures by insulators (Fig. 3).

The design of such insulators is critical. Providing glazing is not used an alumina insulator will stand 100 kV/cm if it is designed carefully[4]). Brave new designs may begin to incorporate insulators in the resonators thus greatly simplifying mechanical design.

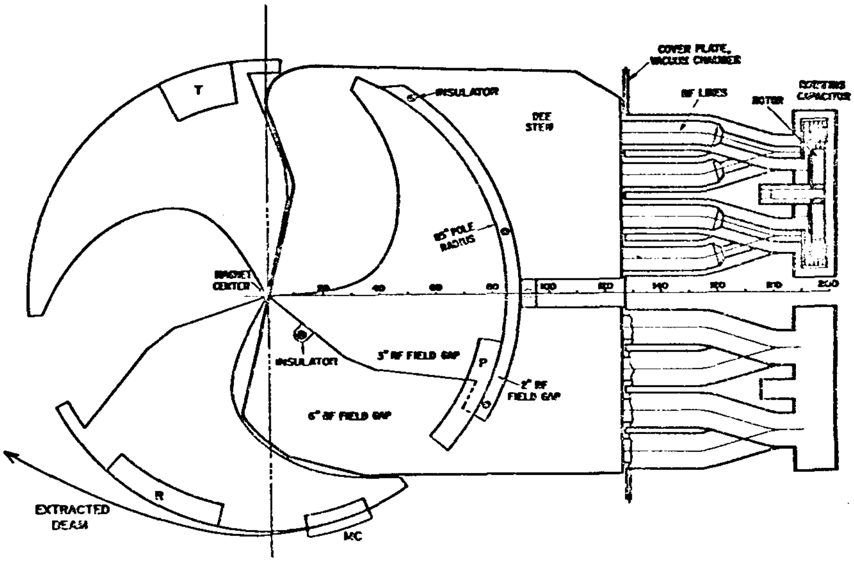

Fig. 3 : Cross sectional view of the Columbia synchro-cyclotron showing the position of the pole shim supporting insulators.

Tuning of the systems is done in various ways. Coarse tuning is accomplished by changing the D impedance or length or by addition of lumped capacitance or inductance at the correct position. Since such effects can be combined it is possible to construct a resonant system that is tuned to not only the fundamental rf frequency but also higher harmonics so that the rf wave shape can be altered by a proper choice of driving circuitry. The TRIUMF rf system was tuned to the first and third harmonic simultaneously in this way. An example of the kind of mechanical structures which are developed to allow for a broad range of frequencies is seen in the diagram (Fig. 4) of a cavity proposed at Oak Ridge for a wide frequency change.

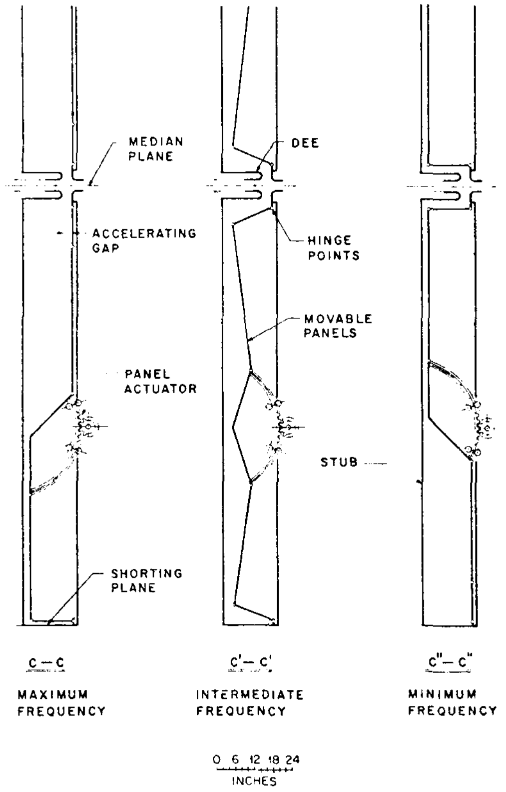

Fig. 4 : Mechanical schematic of a method of changing the cavity impedance distribution and hence its resonant frequency

Hinge design and cooling is critical in such complex folding structures and usually foils are used to maintain good low resistance high frequency connections.

Finger stock is still the most reliable method of connecting a variable shorting plane in the D. A low resistance surface contact and sufficient pressure to maintain this condition leads to a simple movable connection. A 2 mm wide silver plated contact finger on a silver plated cooled surface will reliably pass 10 Amp of rf at 20 MHz. Elaborate systems of silver graphite buttons with pressure systems designed for high contact pressure have been used and are a feature of Philips cyclotrons. These give a high reliability although they are more complicated than the finger stock designs. No connections have been designed which allow a frequency change under power.

Coupling

Either capacitive or inductive coupling seems to be satisfactory for supplying the power to the resonator system. The mode of coupling has been altered in some cyclotrons during the life of the machine and it is difficult to determine which mode works the best as most of the operators claim an improvement has occurred in going from one mode to another. Some cavity designs preclude the use of certain coupling techniques. The SIN cavities are much more easily coupled inductively than capacitatively. All such couplings are subject to the high voltage transients that occur during spark over at the accelerating gap and various techniques are used to prevent spark over across the feedthrough insulator. The weakest point (electrically) in most coupling schemes occurs at this insulator and cylindrical or conical feedthroughs give much stronger connection than disc types. The stresses produced in mounting in conjunction with dielectric shock during spark over requires a careful design to prevent fracture of the window during resonator malfunction.

Connection to the power amplifier is made by means of a co-axial line. This line may be very short if the final power stage is close to the cavity or long if the geometry or future radiation levels do not permit a short connection. In the AEG cyclotrons the problem was solved by the use of a half wave line through the middle of the magnet pole face. In general a high standing wave ratio exists on such coupling lines and indeed may be useful in matching the plate impedance of the tube to the load resistance of the resonator. The high Q of the resonators makes the coupling critical andbad mismatches can occur during ion loading and multipactoring in the resonator system at turn on. During these conditions parasitic frequencies can develop which lead to overstressing of the components in the coupling networks. Plate dissipation can also be exceeded during these conditions and a safe design is one in which the detuning does not lead to over dissipation. The starting assumptions in the rf systems are thus different from those commonly used in commercial radio transmitters and a cyclotron radio frequency art has developed which seems a bit strange to a standard rf engineer. A synthesis of techniques has been achieved in some places and the smooth operation of the Harwell VEC which uses a standard broadcast transmitter as a power amplifier is a good example of such a synthesis.

Power Tubes

The design of power amplifiers has been greatly simplified by the modern high power high reliability military specification tubes which are available to the designer. The service life ratings of some of these tubes are impressive as 15,000 hours is a mean life expectancy for modern long life cathodes. Package sizes have also decreased. A modern high frequency tetrode such as the Eimac 4CW 100,000 E will only occupy a space of about 20 cm in diameter and 25 cm in height and yet be capable of delivering 200 kW of output power at 50 MHz. Similar size reduction, increase in plate power handling capability, and long life is available in tubes from most of the major manufacturers. In a time of increasing prices it is also nice to see the cost per kilowatt of rf power going down in these components.

The noise levels in such tubes have also undergone sizable reductions. Tubes are available in which -80 db noise figures are attainable. This is accomplished by good cathode design and DC heaters. Noise level is further decreased by the use of screen modulation in tetrodes and by series regulation in triodes. The radio frequency voltage amplitude can thus be stabilized or programmed at a level which is required for good energy resolution. Cyclotron rf designers can learn from radio communication techniques in this area.

The availability of broadband solid state transistor amplifiers aids greatly in the design of the power amplifier driver circuitry. Bandwidths of 100 MHz up to power levels of a few hundred watts help to raise the power levels of the frequency synthesizers used to provide the basic system frequencies to the levels necessary to drive the power amplifiers. The generation of parasitic oscillations is reduced in such systems as front end effects can be ignored and more effort put into the high level hardware where modelling is the only safe way to design the system.

Control Systems

Single turn extraction and high energy resolution demand voltage stabilities of a few parts in 10^5 and frequency stabilities of a few parts in 10^6 in the sector focussed machines. The proposed addition of harmonics further adds the even more stringent demand of good phase stability and controllable phase and amplitude variation in the harmonic circuitry. Considerable amounts of reactive power may be required to stabilize the system. In this area the good high frequency performance of integrated circuitry is a great help.

Instabilities arise from the vibrations induced in the resonators through cooling water flow or mechanical pumps fastened to the tank in critical places. Thermal distortions caused by changes in cooling water temperature and power level changes are slower and can usually be taken care of by servomechanisms driving the tuning elements. Panel vibrations which are generally much higher in frequency can only be cured by reducing the cooling water noise by proper pump and piping design. Flow velocities should be kept low and careful attention must be given to turbulence inducing bends and junctions. In addition it may be necessary to add coulomb dampers to the resonators at appropriate points to mechanically damp out unwanted panel vibrations. Such dampers are common in many mechanical systems but have been unnecessary in early cyclotron design. Such techniques have been used at the TRIUMF cyclotron to reduce mechanical vibration effects to a few kilohertz in a resonator frequency of 23 MHz where they could easily be handled by reactive currents in the power amplifiers. If resonators can be made sufficiently stiff and massive such as the SIN cavities such problems do not arise.

The use of solid state phase shifting networks of large bandwidth and high frequency response has aided greatly in obtaining parasitic free feedback control (Fig. 5). The use of such circuits along

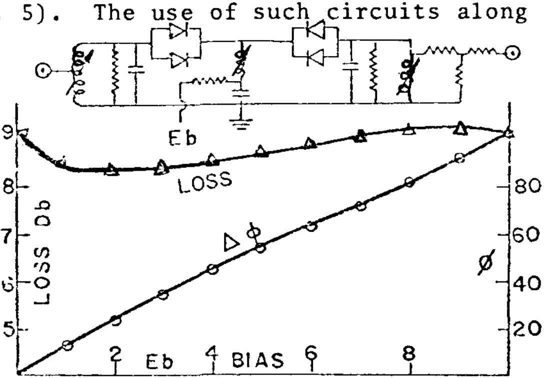

Fig. 5 : A varactor diocle phase shifter and its control characteristics

with sensitive phase measurement techniques allow both the measurement and adjustment of the rf phase to a few tenths of a degree between the various harmonics[5]).

Power Supplies

The cyclotron rf engineer is faced with a unique problem in power supply design. To prevent costly tube failure in his power amplifier he must install a crowbar circuit to remove the HT from the anode in case of spark over, punch through, or destructive parasitic mode onset. Such a circuit which uses a high power ignitron will normally short the output of the anode plate supply to ground in a few microseconds. The transformer and rectifiers must carry this overload for the length of time that it takes for the primary circuit breaker to open. In a cyclotron such a condition may be repeated several hundred times during conditioning and commercial transformers and circuit safety factors are not adequate for such operation. It is important to provide transformers in which the core is braced solidly enough to withstand the numerous shocks such short circuits produce in the structure and attention must be paid to the primary short circuit impedance and secondary short circuit resistance if core failure is to be avoided. Few commercial power supply manufacturers have adequate experience in cyclotron rf systems to provide adequate units.

Trouble Shooting and Tuning

The task of the engineer is greatly simplified by the excellent new radio frequency analyzing instruments. The use of the self excited oscillator and the neon tube detector has been supplanted by the vector impedance meter, the broadband rf voltmeter and the frequency synthesizer. The nature, magnitude and location of system resonances has become a relatively routine procedure. A careful search can be made over the whole radio frequency spectrum required for the safe operation of the machine and with the ability to distinguish series and parallel resonances and their magnitudes the system can be cleaned up by the standard time honored techniques of resonance shifting by configuration alteration or resonance elimination by parasitic circuit insertion. Anyone who has tried to tune a system such as the CERN MSC with its sophisticated rotating condenser (Fig. 6) can appreciate the advantage of such technical aids. The one drawback of such devices among which one should mention the high frequency oscilloscope, is the temptation to improve a working system. Radio frequency electric fields flow in regions where no conductors exist. Changing the position of a conductor may drastically alter a field pattern in a region and a stable system for no apparent reason suddenly becomes unstable or fails completely. The old adage of all good rf engineers still applies: "If it isn't broken, don't fix it!"

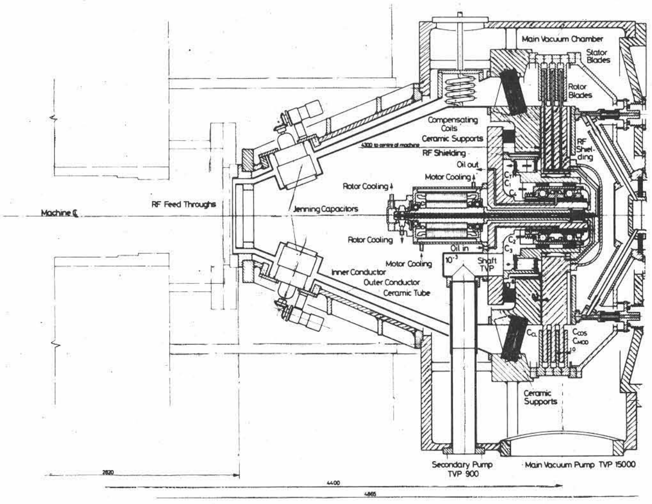

Fig. 6 : The ROTCO of the improved CERN synchro-cyclotron

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