Rutherford Laboratory

Technical Leaflet

A7

NIMROD R.F. SYSTEM AND BEAM DIAGNOSTICS

The Acceleration System

The protons achieve their high energy by passing more than one million times through the Accelerating Cavity, which is situated in the magnet ring. The cavity provides an alternating electric field in the direction of the protons' motion such that those passing through it at the correct time receive an impulse of about 6000 volts in the forward direction on each revolution.

As a result of each such impulse, the protons' velocity increases, and this requires that a) the magnetic field must increase so as to keep the orbit radius constant, and b) the frequency of the cavity's accelerating field must increase to stay in synchronism with the protons' rotation. Typical valves are shown in the accompanying table. In practice, the magnet field is arranged to rise approximately linearly at a rate controlled by the generators and rectifiers, and the accelerating frequency is controlled by an open-loop servo from a search-coil measurement of magnetic field.

	Electron volts	Velocity Vel. of Light	Frequency	Magnetic Field
INJECTION ENERGY	1.5×10^7	0.17	358 Kc/s	300 gauss
FULL ENERGY	7×10^9	0.996	2.01 Mc/s	14000 gauss

The Acceleration Process

The magnetic field determines the timing of all the processes involved in injection and acceleration. By connecting the generators across it through rectifiers, the field is made to rise to 14 kilogauss in 0.7 seconds, after which time the rectifiers are phase-inverted and the stored energy returned to the generator flywheel set. This inversion takes 1.3 seconds, so the whole process is repeated at a rate of one cycle per two seconds.

The injector provides a beam of several milliamps of protons at 15 million electron volts energy, injected tangentially at the outside edge of the ring vacuum chamber. When the magnetic field has reached a value (298 gauss) such that the injected protons would be bent into a circle whose radius equals that of the outside edge of the chamber, the injector is switched on and protons are accepted into orbit. The accepted particles spiral inwards as the field increases, and injection continues until the orbit reaches the centre of the aperture. This filling process stores up to 300 turns of protons, giving a circulating current of about one ampere. Depending on the rate of increase of field chosen, the time taken is between 300 microseconds and 1 millisecond, the time for one revolution being 2.8 microseconds.

At this time the acceleration commences and the injector beam is switched off. The frequency of rotation of the protons at the start of acceleration is 358 Kc/s, and the frequency of the accelerating waveform must be adjusted with considerable precision to be equal to some harmonic of this. In NIMROD, the fourth harmonic is used. There are thus four sectors in the circulating ring of protons, for which the accelerating field is in the correct direction, and protons in these four sectors are accelerated, the remainder being decellerated and collapsing to the inside wall of the chamber as the magnetic field increases. For a given rate of increase of magnetic field, the protons must receive exactly the correct increase in energy per revolution in order to remain at constant radius. The voltage accross the cavity to which this corresponds is known as the synchronous voltage, and the phase of the waveform at which it occurs is the synchronous phase angle (fig.1). An intrinsic property known as Phase Stability provides that for any proton arriving between ϕ_1 and ϕ_2 there is a greater or lesser acceleration tending to move that proton in phase towards ϕ_3. The result is a bunch of protons between ϕ_1 and ϕ_2 , all oscillating about ϕ_3, and all thus receiving, averaged over one oscillation, V_S per revolution.

The accuracy in frequency must nevertheless be great, since an error in frequency will cause a change in orbit radius (and consequent loss of particles to the walls of the chamber) in order to comply with the phase stability conditions.

The frequency is programmed to increase initially in proportion to the magnetic field, this proportionality falling off at high energies as the protons approach the speed of light. At 7 thousand million electron-volts they are travelling at more than 99 per cent. of this speed, 186,000 miles per second, and are orbiting at over two million revolutions per second. At this speed, according to the Special Theory of Relativity, they have eight times the mass of stationary protons.

The Acceleration Equipment

The elements of the system are shown in fig.2. A voltage proportional to the rate of increase of magnetic field $\frac{dB}{dt}$, is obtained from the search coil within the magnet gap. This is integrated to give B, and this is used to frequency modulate the master oscillator, whose modulation characteristic obeys the required frequency - field law (fig.2,3). Modulation is by progressive saturation of the ferrite core in the oscillator coil, thus reducing its inductance, the exact shape of the characteristic being adjusted by passive networks. Final shaping is carried out by the curve corrector, which is an arbitrary function generator also driven by the B signal. The accuracy in frequency required is ±0.02 per cent.

The frequency range (at fourth harmonic) is 1.43 to 8.01 Mc/s, and amplification is by a suitable broad-band amplifier whose final output to the cavity is 60 Kilowatts. The cavity is tuned automatically to the frequency at which it is driven. This tuning is by progressive saturation of its ferrite core by bias windings, the current being obtained from a discriminator which compares anode and grid phases of the final output valves. The closed-loop servo thus formed holds this phase difference at 180°, and hence holds the cavity resonant at the drive frequency.

The cavity contains six tons of ferrite and is water cooled. At 8 Mc/s the bias current required for tuning is 800 amps at 50 volts.

Beam Current Measurement

The number of protons circulating at any time is measured non-destructively by a set of induction electrodes situated in a straight section. As the beam bunches pass through them, a charge and hence a voltage pulse is induced proportional to the quantity of charge present. The train of pulses thus obtained is taken through a wide band amplifier system and displayed in the control room. The electrodes are split radially so that the difference between induced pulses is proportional to radial position of the beam.

These signals are processed to give a voltage analogue of beam radius which is used in setting up the accelerating frequency programme.

Beam Control

An important feature of this machine is an automatic system for regulating the beam's progress during acceleration. Departures of the acceleration frequency from the correct law cause changes in orbit radius and consequent loss of protons to the chamber walls. The Radial Control measures the orbit radius by electrostatic induction and provides the oscillator with a control signal. This forms a closed-loop servo which stabilises the orbit radius to within two centimetres in an aperture of one metre with the result that beam losses are considerably reduced and the oscillator settings become non-critical.

A further closed loop servo prevents disturbances in the phase motion which might otherwise force protons beyond the limits of phase stability. This also has caused considerable reduction in beam loss.

These servo controls contribute largely to the high output beam currents obtained, and render the beam very insensitive to errors, maladjustments and interference.

Diagnostics

The rapid and successful commissioning of the machine has been facilitated greatly by the comprehensive set of beam tracking and measurement equipment installed. The induction electrodes provide a display of circulating current and beam position during injection and acceleration, whilst remote-controlled targets can trace the beam's position round the machine with great accuracy. This equipment incorporates the latest mechanical and electronic ideas, and has stimulated much original work in the industries concerned. An example of this is the target actuator system, a unique digital servo which controls the position of probes to an accuracy of 0.0004 inches in 40 inches, with a maximum power of 3/4 B.H.P. Eight such actuators are fitted, operated from one control system. Position is demanded by a five-decade switch unit, and rotation of the probes as well as translation is provided with similar accuracy.

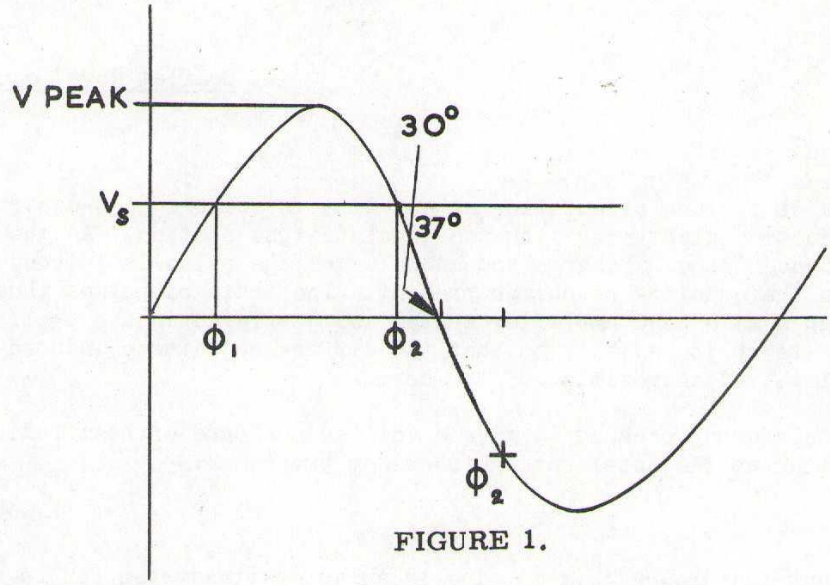

FIGURE 1.

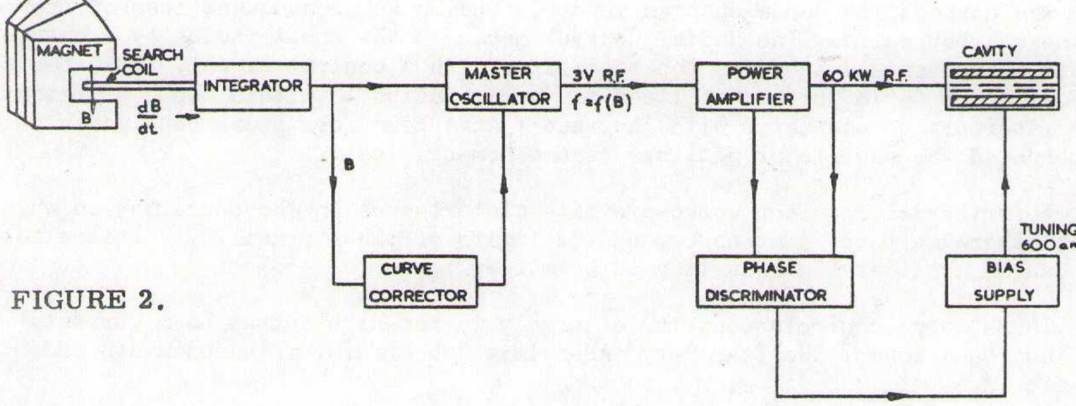

FIGURE 2.

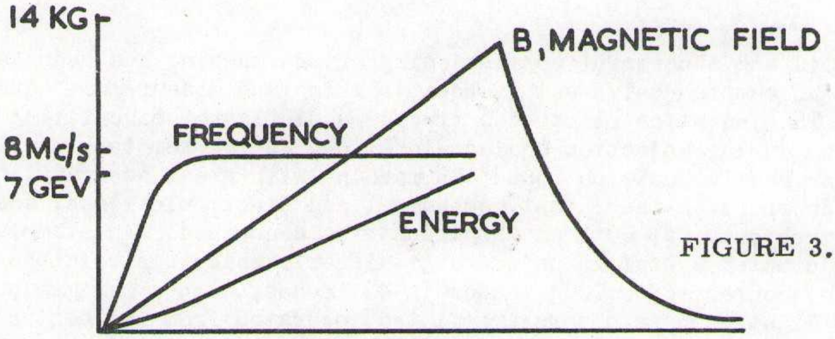

FIGURE 3.

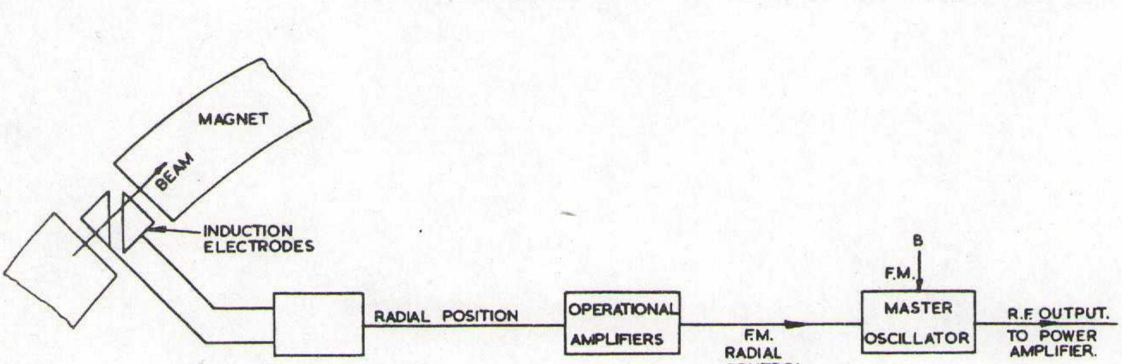

FIGURE 4. RADIAL CONTROL LOOP