A 2ND RF SYSTEM FOR NIMROD

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Summary

An additional high power RF system has been built for Nimrod to provide an 8th harmonic accelerating field i.e. the 2nd harmonic of the main RF. Its purpose is to reduce the bunching factor of the proton beam thus increasing beam acceptance and accelerated intensity. In the accelerating cavity a drift tube is tuned over a frequency range from 2.8 MHz to 16 MHz by two ferrite loaded resonators. The configuration adopted proved to have considerable advantages over a self contained tuned cavity particularly for assembly and access, permitting economy in the use of ferrite. The problems discussed include that of covering a wide tuning range while restricting the magnetic flux in the ferrite, suppressing unwanted modes in the cavity and maintaining accurately the phase and amplitude of the harmonic field relative to the main RF.

Introduction

Up to the present time machine development on Nimrod has not involved major changes to the RF acceleration system. The improvements in quality and intensity of beam have been obtained 1) by modification and reorganisation of the present system such as the commissioning of radial and phase control systems to improve RF capture and facilitate precise steering of the beam, the provision of phase ramping of the de-buncher to improve matching to the machine acceptance, and reorganisation of the pole face winding supplies to increase the useful aperture; and 2) by increasing the efficiency of beam control in the extraction process where methods such as the use of servoed frequency-modulating noise, and the use of thin septum magnets have succeeded in greatly improving extracted beam efficiency and effective spill time. However, as in all accelerators there are space charge forces limiting the intensity of beam which may be injected and accelerated and it is believed that no further increase is possible without modifying these forces[1]. To this end the system described below was designed to add a second accelerating field at the 2nd harmonic of the main RF field. The correct relative amplitude and phase of this field is such as to produce a combined accelerating field as shown in fig. 1a, the harmonic field being produced in a separate straight section one quadrant from the main RF. The accelerated particles receive the same synchronous energy gain/turn but there are now two stable phase angles ϕ_A and ϕ_B, compared with the normal case where the synchronous energy gain occurs at ϕ_S. The effect is to increase the phase acceptance area and to reduce its maximum amplitude as shown in fig. 1b.

Let us define the bunch shape as the factor $\bar{B}$

then $\bar{B} = \bar{N}/\hat{N}$ (1)

where $\bar{N} \propto A/2\pi$ = average particles/unit angle

$\hat{N} \propto \hat{\dot{\Phi}}$ = maximum particles/unit angle

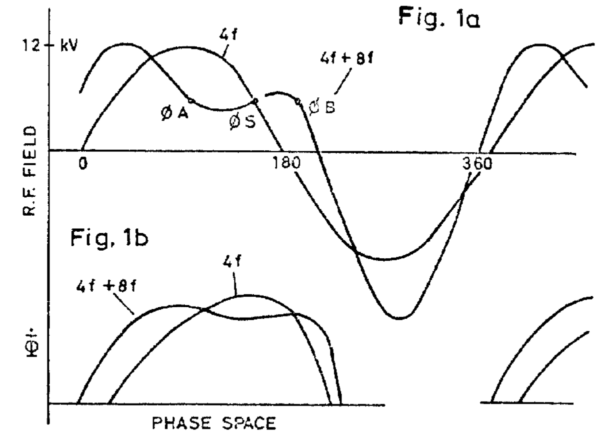
A = phase stable area, $\mathrm{rad}^2/\mathrm{sec}$

$\hat{\dot{\Phi}}$ = peak amplitude of phase stable area rad/sec

so $\bar{B} = A/2\pi\hat{\dot{\Phi}}$ (2)

here it is assumed that the density of particles in phase space is uniform.

$\bar{B}$ defines the inverse of transverse space charge seen by those particles going through the peak values of synchrotron oscillation and hence closer to conditions where loss through betatron resonance is certain. If $\bar{B}$ can be increased then given otherwise equal conditions an equivalent number o particles should be trapped and accelerated. The method has been tried elsewhere[2,3], on an experimental basis, with success.



The system being installed on Nimrod is designed to increase $\bar{B}$ by between $32\frac{1}{2}$ and 47% the actual improvement depending on the programming of the magnetic field during the first 2 msecs of acceleration. As it is intended to maintain the harmonic field throughout acceleration the RF power required is comparable with that supplied to the main RF system. The new system is now being installed during the present annual shut-down on Nimrod. This paper describes the main features of the system, the reasons for their present form, and some of the electrical problems encountered, it does not describe the vacuum and mechanical engineering problems.

Choice of RF Geometry

Firstly it was decided to use ferrite for tuning purposes as alternative methods of mechanical tuning have at least comparable difficulties. Next a choice was made between 1, a self-contained tuned cavity with a ferrite loaded interior and a re-entrant portion containing the vacuum vessel, and 2, a drift tube structure in which the tuning system consisted of two ferrite loaded resonators in the form of shorted-stub coaxial lines. The dominant problem with both systems was of producing the necessary permeability changes in the ferrite to tune the system over the frequency range required for Nimrod i.e. from 2.8 to 16 MHz. In either system the bias conductors must couple into pairs of ferrite stacks so that induced RF potentials in them can be arranged to cancel by alternating the senses of the conductors. The features of each system are listed below.

1) Cavity

(a) has one gap per cell with the full field available as acceleration potential.

(b) is self-contained with the ferrite mounted around the re-entrant sections containing the vacuum vessel. The stray inductances of the ferrite stacks are thus minimised.

(c) the RF feed to the accelerating gaps adds considerable stray inductance to the final valve structure.

(d) complex decoupling and mechanical shielding is required to keep the bias conductors out of the RF field.

(e) the ferrite stacks must be in frames large enough to contain the vacuum vessel. On a weak focussing machine this is a considerable objection since the aperture is large requiring physically large assemblies.

1. DRIFT TUBE
2. STRAIGHT BOX
3. RESONATORS
4. BIAS CONDUCTORS
5. BIAS RETURN CONDUCTORS
6. FERRITE RINGS
7. SUPRESSION CIRCUIT CONDUCTORS
8. FINAL VALVE POSITION
9. INSULATING SUPPORT

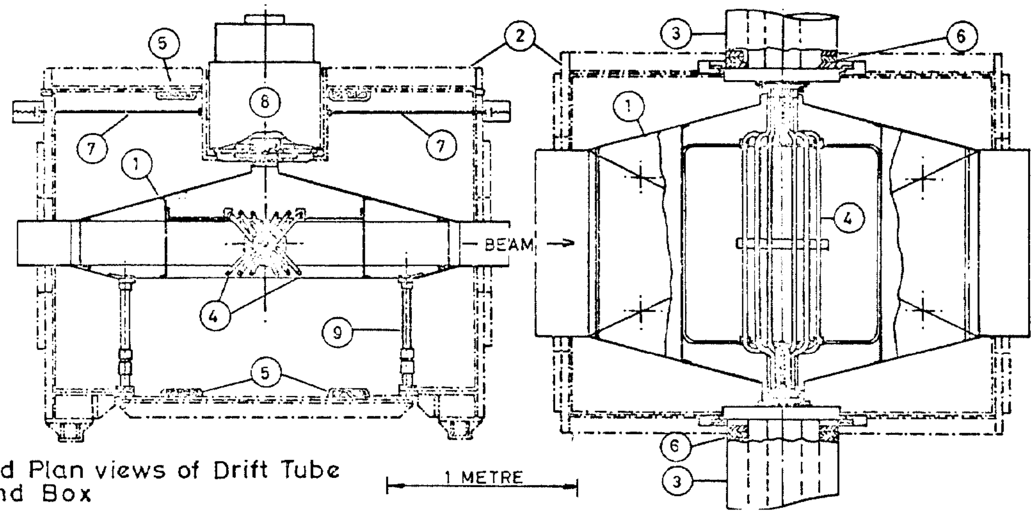


Fig. 2a & 2b. Side and Plan views of Drift Tube and Box

2) Drift Tube with External Ferrite Stacks
   (a) has two gaps per cell with only the time difference voltage available for acceleration, therefore tends to be long (a quarter wavelength for full volts) with a large self capacity,
   (b) stray inductance to the ferrite is larger,
   (c) RF feed to the drift tube can have low stray inductance with the final valve mounted very close to the drift tube,
   (d) shielding of the bias turns from the RF field is complete,
   (e) separated from the vacuum vessel geometry there is considerable choice in the form and volume of the ferrite stacks,
   (f) not being self-contained like the cavity the drift tube arrangement does permit separate fabrication and testing of the main components, a factor of considerable advantage during the construction program.

The drift tube system was chosen features 2d, 2e and 2f being dominant. The requirement was for a tuned system over the range 2.8 to 16 MHz with a peak voltage of 10 KV on the gaps giving an effective 8th harmonic accelerating field to the beam of 8.4 KV peak. i.e. 60% of the main RF field. After a model study the structure shown in figs 2a and 2b was selected. The final valve, a 35 kW air-cooled tetrode, was mounted in a re-entrant well in the top of the vacuum box with the ferrite loaded resonators on either side. The bias conductors were placed in the field free region inside the resonators, traversing the box above and below beam aperture but inside the copper skin of the drift tube. The bias return conductors traversed the top and bottom inside box surfaces underneath RF shields. The whole of the box interior was placed under vacuum to avoid the need for insulating vacuum windows at the drift tube ends and their capacitance.

Ferrite

This choice was a dominant problem having a considerable bearing on the geometry discussed above. Fig. 3 shows the required variation of μ against bias field compared with that of the main RF system, the new system demanded a very wide range in μ. Ideally the resistive load presented by the ferrite to the final RF amplifier should not vary over the band i.e. the $\mu Q\omega$ product should remain constant as the frequency rises and the ferrite is progressively biased. However it is important to obtain this figure of merit from measurements obtained under closely simulated working conditions otherwise it can be grossly misleading. This is illustrated in Fig. 4 where $\mu Q\omega$ under swept and fixed conditions is compared with that measured in the unbiased flux state. Note there is a large reduction in $\mu Q\omega$ when the bias field is swept rapidly during the early part of the acceleration cycle, as found elsewhere[4].

Fig.3

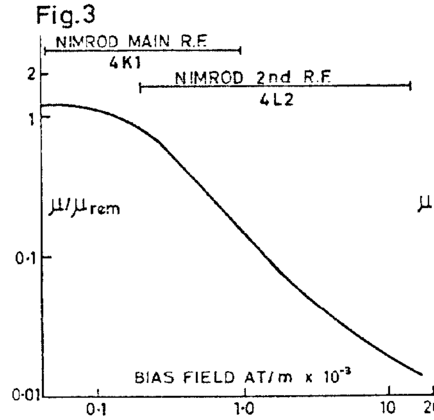
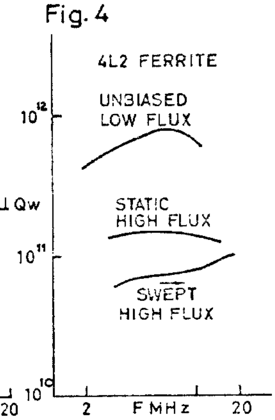


Fig. 4



Another factor which must be accounted for is the variation of permeability with increasing flux density. This can lead to highly unstable conditions as resonance is approached. The normal resonant response curves become lopsided and in the limit it is impossible to maintain full volts, resonance being marked by a jump in RF voltage as the triple value region is crossed[5], (Fig. 5). The effect is not seen under swept conditions as the ferrite losses reduce the flux changes for small tuning errors. At fixed frequency it is apparent but not a serious problem on the drift tube system as the final valve impedance provides sufficient loss to suppress the 'jump' phenomenon. The problem was severe with a test rig designed to measure the μQ at max RF flux in single rings.

The diameter of the foreshortened stubs or resonators was determined by the maximum flux density allowable and Q falls rapidly with increasing flux. The manufacturers experience with large rings used on AG synchrotron cavities as at CERN and Brookhaven was useful here. The ferrite finally chosen was manufactured by Messrs Philips of Eindhoven and was essentially similar to that used on the new RF systems on the CERN PS. Each resonator comprised 26 rings of dimensions .44 m O.D., .25 m I.D. and .025 m thick interposed with water cooled plates of spirally wound copper tube solder bonded and machined to flat discs of 6 mm thickness. Since the resonator forms a shorted coaxial line the RF current varies along its length, with a maximum at the shorted end. Flux density therefore varies with

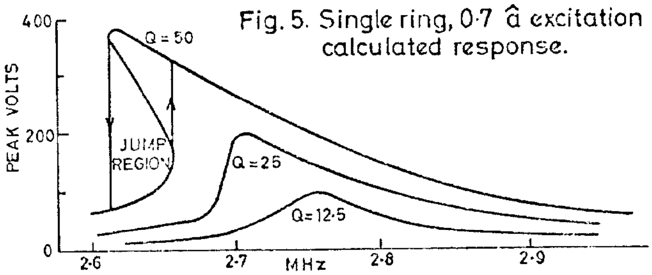


Fig. 5. Single ring, 0·7 â excitation calculated response.

ring position and a careful assessment of these losses was made to ensure that thermal stresses were kept within safe limits.

Final RF Power Stage

A 35 kW RF tetrode was preferred to a grounded grid triode since it placed less load on the preceeding drive stage, thus permitting use of a commercially available 1 kW wide band distributed amplifier as a drive chain. The input capacitance of such tetrodes is high and careful matching to the driver output was necessary to maintain bandwidth. The choice was influenced by the higher power gain obtainable with the tetrode. The load seen by the final anode is shown in Fig. 6.

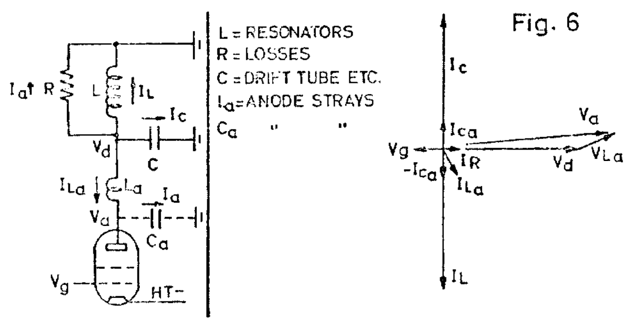


Fig. 6

The stray inductance comprising the valve structure and stem and the re-entrant section must carry at resonance that fraction of the reactive current I_{CA}, flowing through Ca, as well as the loss current I_R. The vector diagram is drawn with the assumption that Vd is held in anti phase with Vg, by the bias loop. There is a considerable voltage drop across L_A due almost entirely to I_{CA} so in practice Va exceeds Vd by about 1 kV peak at resonance. Operating conditions are HT = 13 kV Va = 11 kV Vd = 10 kV, Ia = 1A and 2A (mean) while sweeping. The drift tube and anode are operated at ground potential thus freeing the anode circuit from decoupling problems. This produced a problem in the cathode and heater decoupling which was relatively easier to deal with.

Unwanted Resonant Modes

The circuit shown in Fig. 6 does not apply at higher frequencies. Here the drift tube and box behaves like a series resonant circuit at 32 and 35 MHz. Tuned coupling loops are built into the box to suppress the unwanted modes, the loops being formed by horizontal conductors bridging the space between the valve well and the side and end walls of the box, connecting through the box walls to preset vacuum capacitors with series damping resistors. When these circuits have been properly tuned the unwanted modes are completely suppressed and the final valve operates stably and reliably. See Fig. 2a.

Bias System

In the biasing system 12 turns are arranged in two groups of 6 connected in parallel. As the resonator inners link the ferrite a series decoupling capacitance is necessary at their ends to avoid an effective short circuited turn in the bias load. The Bias Supply comprises a motor generator and a 3000 amp transistor series regulator. A notable feature of the transistor bank is the thyristor crowbar which shorts the collector emitter bus bars if any power excursion in the transistor bank exceeds a predetermined safe level. Further protection of the bias system is provided by a sensitive earth leakage protection system.

The effect of magnetostriction in the ferrite was manifest as a high pitched noise in the ferrite rings. Transfer function measurements of the bias loop showed a pronounced resonance at about 7 KHz corresponding to a fall in reactance of the bias winding and a corresponding mechanical resonance. The effect is so strong it dominates the bias transfer function at all bias fields. It can be suppressed by placing a 1 ohm resistance across the bias turns alternatively or by inserting a trap network, twin or bridge T, in the operational amplifiers controlling the Bias Supply. Various mechanical damping arrangements were tried with little success.

Local current feedback enables accurate control of the starting current before the bias loop is closed at the start of acceleration. It also controls a programmed current so that the ferrite is correctly biased at the rate required for acceleration. The controlling function for this is derived from the primary frequency generator which accurately tracks the machine field. Initial phase errors in the bias loop are considerably reduced by this means.

Transistor failures; each transistor in the bank has its own fuse with a contact to signal a failure remotely. Above a few per cent failure the bank is isolated and the fact indicated, so far despite much hard interrupted experimental usage there have been no trips on transistor percentage failure.

Amplitude and Phase Control System

Given a well behaved ferrite biasing system the accurate maintenance of relative phase and amplitude of the 8th harmonic field is feasible. However cable distances are considerable, unwanted RF currents abundant and there are many potential errors due to other forms of interference. A closed loop phase-locked method is therefore necessary to maintain the desired relationship. For the amplitude control an AGC system functions from the rectified RF potentials at the ends of the drift tube via a semiconductor wide-band multiplier at the input to the drive chain. The phase control system employs considerably more sophistication to compensate the phase discrepancies in the cables and amplifier stages of both the main and the 8th harmonic RF system. The PFG signal is fed to the harmonic drive chain through an AGC multiplier, fast phase shifter, frequency doubler and a digitally controlled programmed phase compensator. The phases of the main and 8th harmonic field are compared in a phase detector coupled to the gap monitors via level control units, matched cables and in the case of the main field, a frequency doubler. In the 8th harmonic side it was found necessary to substitute a simulator based on the doubler circuit but without its doubling action to maintain phase parity under all working conditions. In the fast phase shifter, operation is through a system of wideband semiconductor multipliers operating on phase split signals 90° apart and its range is through ±45° from zero phase shift with a bandwidth of about 50 MHz. A digitally controlled programmed phase unit is employed to switch in discrete delays via semiconductor switches to compensate for the relative phase errors arising during acceleration out of the range of the fast phase shifter.

RF Discharge

The RF conductors in the resonators and final valve housing are in air and present no unusual problems. In the box, however, the vacuum conditions present an additional source of discharge, i.e. multipacting or electron resonance where electrons accelerated in a low RF field have the numbers and phase for a sustained discharge. At the start of acceleration normal operation is not affected, the RF potential on the drift tube rises in a few microseconds during turn on, through and above the multipactor zone to 10 $\hat{KV}$. The zone boundaries rise with increasing frequency and as 16 MHz is approached there is less margin against discharge. When the drift tube system was first operated under vacuum the multipactor zone boundary was explored by lowering the potential until discharge occurred. At this stage the vacuum was not good and the electrode surfaces unconditioned, next carbon black was applied to the drift tube to reduce its secondary emission coefficient and the boundary was remapped. Finally the carbon black was removed and a conditioning process evolved in which the drift tube was operated at just above discharge level, here the vacuum pressure would rise as adsorbed gases were released; thus conditioned a further reduction of RF potential was possible. After several hours of such work the drift tube could be operated at all frequencies with a substantial margin above the discharge levels. Work is proceeding with electrodes mounted on the box walls and biased with a high DC potential to further inhibit the phenomenon.

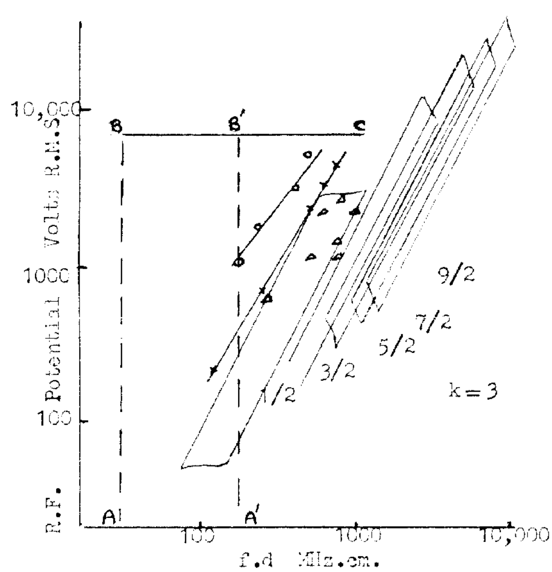


Fig 7 Measured discharge limits compared with calculated zones published in Ref 6 on parallel plate Al electrodes

The measured discharge levels are plotted in Fig. 7 on a chart due to Hatch[6] which gives the multipactor zones for parallel plate aluminium electrodes in vacuum where these zone boundaries are calculated from relationships as in the equation below for the lowest $\frac{1}{2}$ cycle mode.

$$\hat{V} = 4\pi f^2 d^2 / \{e/m[(k+1)/(k+1)]\pi \cos\phi + 2 \sin\phi\} \qquad (3)$$

where $\hat{V}$ = peak RF volts
f = frequency
d = electrode spacing
ϕ = electron phase

in eqn. (3) it is assumed the emitted electrons leave the surface at a certain fraction, $1/k$, of the incident electron velocity, which has been found to be independent of the type of electrode materials used. Eqn. (3) defines the electron phase boundaries for multipacting, the upper and lower boundaries of each zone being determined by the secondary emission yield curves for the materials used.

Normal operation is shown by the shaded area, AB, A'B', where the drift tube potential across the respective minimum and maximum 'd' values rises rapidly during turn on and the line BB' to C where the voltage is constant at 10 kV or 7.0 kV rms. The results of unconditioned and conditioned measurements are plotted and show interesting correlations with the mapped zones. The $\hat{V}$ against f^2d^2 relationship is confirmed for the unconditioned and carbon-blacked states and in the conditioned states it appears the copper surfaces of the drift tube and box are considerably better than in the theoretical care for aluminium.

Acknowledgements

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