NIMROD - PRESENT PERFORMANCE & PROPOSED DEVELOPMENT

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1. INTRODUCTION

There seem to be no reasons why Nimrod, as it exists now, should not run satisfactorily at an intensity in the region of 2×10^{12} protons per pulse for about 10 years, the period determined by radiation damage to the vacuum vessels. To increase the intensity to 10^{13} p.p.p. or more will require many changes, the most important of which are discussed briefly in this report.

2. BEAM INTENSITY

Nimrod (1) reached its design intensity of 10^{12} p p p in September, 1964, 12 months after commissioning, and normally runs at approximately 1.5×10^{12}. Recently, levels of about 2×10^{12} have been observed but the conditions favourable to these enhanced values have not yet been determined.

Application of Lasletts's formulae (2) for the transverse space charge limit with a perfectly conducting vacuum envelope indicates that 7×10^{12} protons circulating at 15 MeV would shift the working point to $Q_r = 0.5$. Allowing 20% trapping by the r.f., and assuming that energy spread prevents the phase motion leading to any further increase in charge density, the expected intensity limit would be about 1.4×10^{12} p.p.p. The transverse resistive instability has been observed but is not normally present, and can presumably be largely eliminated by a suitable damping system (3); such a system is now being constructed.

These theoretical limits are regarded as approximate only, but we feel, nevertheless, that it would be unrealistic to suppose that levels above 3×10^{12} will be easily attained with the existing equipment, although the present r.f. system should not limit intensities to below 4×10^{12} p.p.p. and the injector beam is adequate for levels well above 10^{13} p.p.p. ignoring the various space charge limits. Studies are continuing, which, it is hoped, will lead to a proper understanding of the phenomena occurring in the beam during injection and trapping.

It would undoubtedly be possible to raise the intensity above 10^{13} p.p.p. by using an r.f. system of tor energy (4) and by using an r.f. system of suitably higher power (5). Design studies for this work have begun but before actively embarking on such development it will be necessary to find ways of operating Nimrod efficiently in the face of the difficulties likely to arise from residual activity and radiation damage.

One very attractive method of increasing injection energy would be the use of a separated orbit cyclotron (SOC) to boost the present injector energy of 15 MeV to about 70 MeV (6). In the proposed booster, twenty four magnets using alternating gradient pole pieces constrain the beam to pass through twenty four r.f. cavities, the beam making seventeen passages through each cavity in passing to full energy. Three of the r.f. cavities are used for control of beam loading effects. A constant turn spacing is achieved by increasing the cavity voltage with radius, thus simplifying the design of the magnet poles

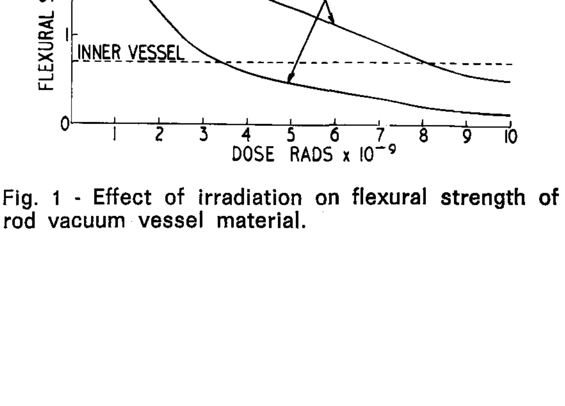

Fig. 1 - Effect of irradiation on flexural strength of Nimrod vacuum vessel material.

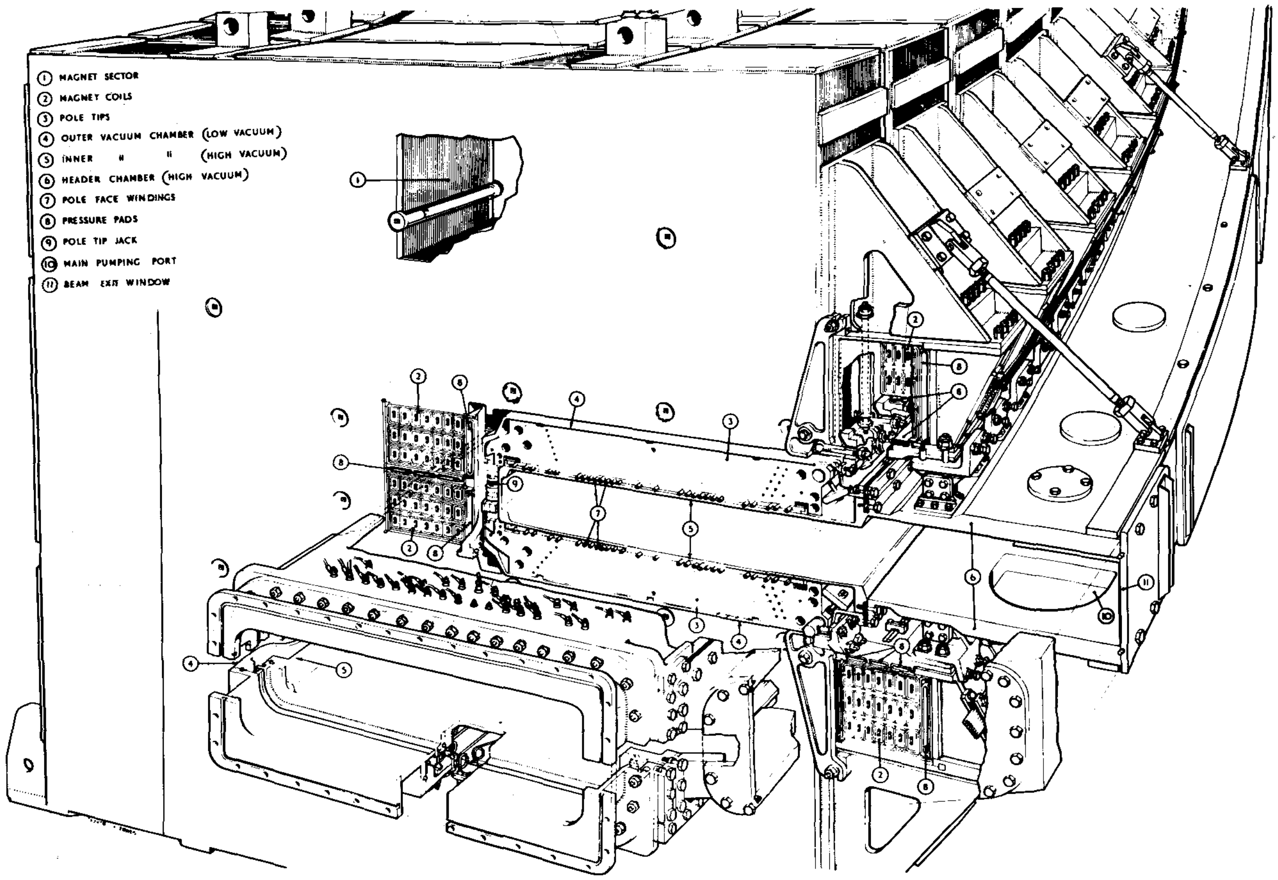

Fig. 2 - Nimrod magnet - vacuum vessel assembly.

as the mean field strength in each pole is held constant at about 7 kG.

Operated at the same frequency as the linac, and in the same mode, the r.f. power amplifiers will provide both phase and amplitude control over the fields in the cavities, an essential feature in view of the extremely heavy beam loading occurring at full current.

TABLE I

Proposed SOC injector parameters

Machine		
Field strength	7.0	kG
Mean gap	4.0	cm
Total magnet power	230	kW
Total magnet weight	150	t
Turn spacing	12	cm
Gap voltage, max.	300	kV
Frequency	115	MHz
Cavity power, full beam	480	kW/cavity
Max. radius, 70 MeV	3.7	m
Orbit		
Q_v, Q_r	4	
Acceptance, max.	150	mm mradian
Emittance at 70 MeV	20	mm mradian

Two proposals are being considered for a possible higher power synchrotron r. f. system, both retaining the present ferrite loaded cavity. A power level was chosen to accommodate 2×10^{13} particles at which point the maximum power delivered to the proton beam is of the same order as the power dissipated in the cavity ferrite. The first proposal is for a conventional higher power system, replacing the present output triodes by higher power tetrodes and using a higher power drive chain. In the second proposal a coupling loop is introduced in the cavity ferrite and the cavity operated as the resonant circuit of an oscillator.

3. INDUCED ACTIVITY

Radiation levels in the circulation space round the magnet at the commencement of a normal shut-down period are generally close to 2.5 mrem/h with local hot spots up to 20 mrem/h, and therefore present no special problem. Inside the vacuum vessel the level is about 25 mrem/h away from components which intercept beam e.g. targets, inflector, extractor magnets. Ho-

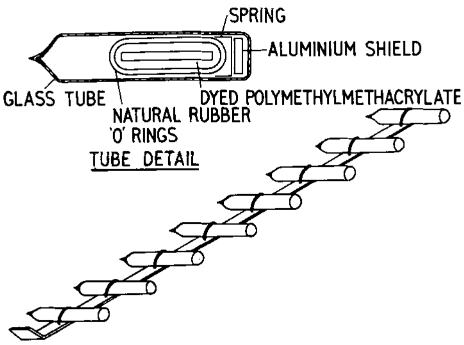

Fig. 3 - One form of dosimeter assembly.

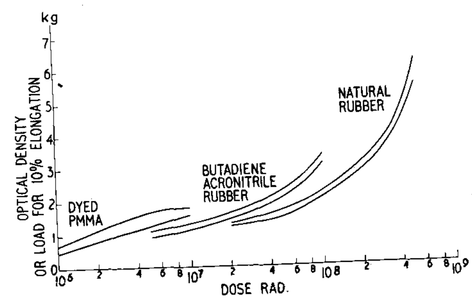

Fig. 4 - Characteristics of dyed perspex and rubber dosimeters. (Double lines give 95% confidence limits).

wever, close to the surface of such components, levels up to 100 rem/h may be found and work has been necessary in certain straight section boxes in fields of 100 mrem/h. With a probable normal intensity of 2×10^{12} p.p.p. and with shorter, less frequent maintenance periods in future, we anticipate that these radiation levels will increase up to fivefold within the next year or so. Considering that Nimrod's components were not designed, in the main, for active handling, such levels are expected to place severe, but probably just tolerable, demands on available staff and the presently planned active workshop facilities.

Many of the machine's components are, in common with those of other big constant gradient synchrotrons, large as well as of complex design and are not at all suited to modularising and to manipulation using remote handling techniques. The problems of dealing with the levels of activity which would accompany intensities of 10^{13} p.p.p. or more are thus most formidable and we are only just beginning to grapple with them. If we can develop an extraction method whose efficiency exceeds 90% then the internal targets could be restricted to an allocation of 10^{12} p.p.p. and the activity problem transferred to the experimental areas where it can be dealt with relatively easily. Even with somewhat lower extraction efficiency, and the same restriction on internal targets, the activation problems might be sufficiently confined in the number of affected components, and in location, as to be tractable. Studies are now in progress directed towards obtaining higher extraction efficiency than that of the Piccioni method.

4. RADIATION DAMAGE AND DOSIMETRY

Reduction in the useful lifetime of the epoxy resin/glass fibre vacuum vessels (7, 8) by radiation damage was recognised at an early stage as being a likely limitation on machine operation. Il was believed that the strength of suitable resins would be affected by a dose of about 10^9 rad and the initial theoretical assessment suggested that such a dose would accumulate in 2-4 years (9). The resin formulation used in the vessels was selected following an extensive series of irradiation experiments, using, for the most part, 4 MeV electrons, to determine the effect on flexural strength. Repairs to the manufactured vessels were necessary to eliminate locally damaged or leaky areas, and had of necessity to be made with material inferior to that of the main construction. The reduction of flexural strength with irradiation dose is shown in Fig. 1. It was concluded from a detailed analysis of stress distribution in the vessels (10) that, allowing a safety factor of 5, the minimum flexural strengths required for satisfactory use are 2,100 kg/cm^2 and 700 kg/cm^2 for the outer and inner vessels respectively, corresponding to maximum doses of 0.8×10^9 rad and 3.3×10^9 rad respectively.

From the outset an extensive programme of radiation dosimetry was applied to the vessels and the magnet throat region generally and continues to be developed (11). The arrangement of the vacuum vessels and other components around the magnet throat is shown in Fig. 2.

A large number of dosimeter assemblies, (Fig. 3), are installed in the machine, mainly on the inner vessel floor, and are removed regularly for measurement. The techniques in present use depend on the increase with irradiation of the optical density of dyed perspex and the increase in elastic modulus of natural and butadiene acronitrile rubbers (Fig. 4). These together cover the range from 10^6 to 5×10^8 rad. The dosimeters are shielded sufficiently to eliminate penetration by low energy protons. The very large number of injected protons which are not accelerated are prevented from reaching the vacuum vessel laminate either by numerous trimming screens or because their angles of incidence are too low for penetration through the 0.005 cm stainless steel lining of the inner vessel. In addition to these dosimeters there are several hundred panels of vacuum vessel material which will be progressively removed for destructive testing when the dosimeter measurements indicate that the vessel dose is approaching the threshold for damage.

The limited time available to remove, measure and replace dosimeters during maintenance periods does not allow a simultaneous complete record of dose distribution to be obtained - it would take 1,000 man-hours to obtain data from some 1,000 samples. Simple dosimetric systems which will give a remote reading without removal are therefore being investigated. Promising results are being obtained using the change in electrical conductivity with radiation dose of certain solutions; it seems likely that this will provide the basis of a dosimeter for the range 10^6-10^9 rad.

Typical measured inner vessel dose distributions are shown for one octant in Fig. 5 and isodose contours for the whole machine in Fig. 6.

Results are broadly as would be expected from the early theoretical predictions of the behaviour of protons after passage through targets (9), although the target parameters assumed do not closely resemble those eventually used. The peaking in the radial distribution towards the inner radius arises from the vertically defocusing magnetic field encountered by the protons after they have lost energy in the target: the structure in the azimuthal distribution can be correlated for the most part with the targets used, taking into account their position and physical characteristics. No detailed analysis has yet been made of these results, but it is clearly important to develop the ability to predict the dose distribution which will result from a given target utilization schedule.

Fig. 7 shows how the inner vessel dose and the number of accelerated protons have increased with time; the plotted doses are the maximum values recorded in the octant. The dose curves are sadly lacking in detail as a consequence of our inability to measure all the installed dosimeters simultaneously, but they illustrate clearly that radiation dose is closey following the ge-

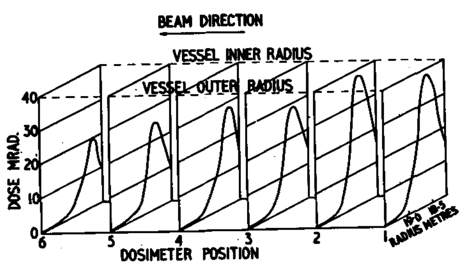

Fig. 5 - Typical dose distribution in octant.

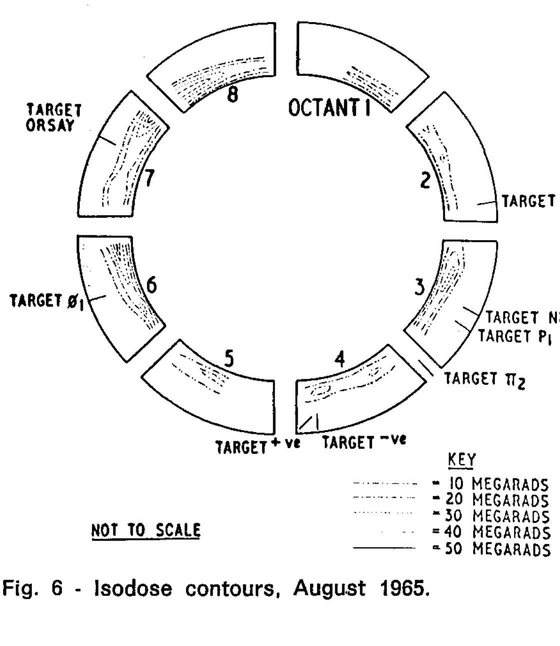

Fig. 6 - Isodose contours, August 1965.

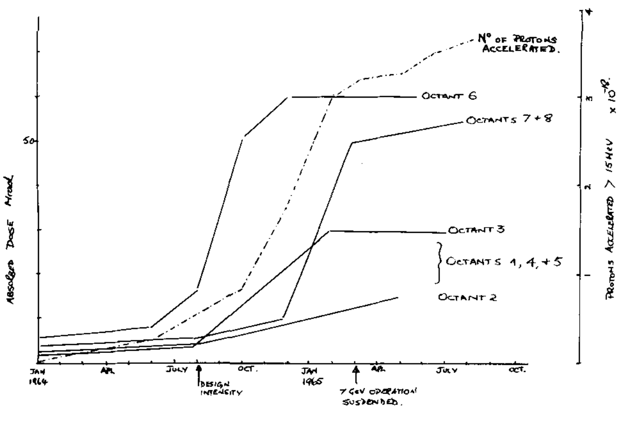

Fig. 7 - Growth of dose and number of accelerator protons.

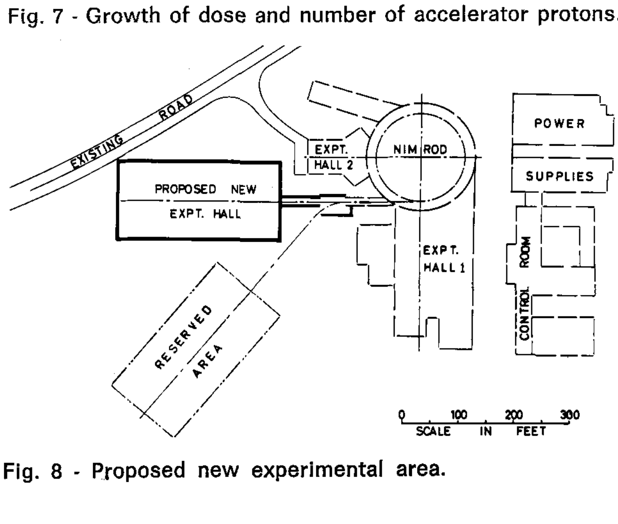

Fig. 8 - Proposed new experimental area.

neral trend of total accelerated protons and that the shift of the dose incidence from one octant to another follows changes in the pattern of target utilisation. We can use these results to estimate the useful life of inner vessels. A rather crude figure based on an average dose rate can be obtained by linking the maximum dose so far observed anywhere, 60 Mrad, with the number of protons accelerated to 7 GeV to date, 3×10^{18}, at the same time allowing for increased intensity and utilisation in future (2×10^{12} p.p.p, 25 p.p. min, 240 days/year, 85% efficiency). This yields a figure of 11.5 years to reach the previously stated limit of 3.3×10^{9} rad for failure of the repaired laminate. If all the radiation dose is concentrated in one or two octants, however, as would follow the exclusive use of a single target, the lifetime is more correctly estimated from the steepest slope of the curves at about 7 years. The importance of target diversity is clear.

We have concluded that there is no need to provide a complete set of replacement inner vessels for continuing operation at the levels of intensity likely to obtain for the next 5 years. The laminate, and particularly repair laminate, may develop leaks but we believe these could be repaired *in situ*: in any case we have two spare inner vessels. Increased outgassing of the laminate is expected in time but is unlikely to exceed twice the design figure at 10^{9} rad and this should be within the capacity of the pumping system; more information is needed on outgassing at higher doses.

Access to surfaces of outer vessels is greatly limited by the geometry and, consequently, their dosimetry is much less comprehensive than that for inner vessels. Such measurements as are possible, together with theoretical predictions based on inner vessel doses, lead us to believe that the outer vessel lifetime will be comparable to that of the inners: again, there is no need for a new set of vessels in the near future.

There are many other radiation sensitive components in the magnet/vacuum vessel assembly, but the only ones believed to be in need of improved design for present intensity levels are the terylene-reinforced PVC nitrile pressure bags which restrain the main coil assembly, and certain other solid coil packing pieces. It is intended to replace these pressure bags by a more resistant form within the next 12 months; they can be installed without dismantling the vacuum vessels and coil assemblies. The solid packing material will not be replaced unless it fails in use.

Epoxy materials are now available commercially, (e.g. Ciba MY 1020), which, if used to construct a new set of vacuum vessels, would yield a system of at least 10 times the present radiation resistance. Polyimide materials, which might be used but whose feasibility for this application is not yet established, are reported to have better radiation stability still (up to 10^{12} rad) and the use of ductile ceramics (e.g. polyphosphates) might enable the production of vessels completely stable to radiation. We believe that the resistance of the other radiation sensitive components in the machine could also be increased sufficiently by appropriate redesign and material substitution, to withstand operation above 10^{13} p.p.p.

5. EXPERIMENTAL AREAS

Congestion of beams in the experimental areas is leading to inefficiency, particularly because it is often difficult or impossible to instal a new beam without affecting other beams already in use. In order to reduce this congestion and also to utilise more fully the available total beam hours an additional area of 4,200 m^2, to be served by a second extraction system, is now being planned for construction to begin in 1966 (Fig. 8); it will double the total space available.

6. CONCLUSION

The intensity limit for Nimrod in its present form is unlikely to exceed 3×10^{12} p.p.p. Operation is likely to be restricted to about 2×10^{12} p.p.p. for the next few years since such a level is consistent with an acceptable life for the reinforced epoxy vacuum vessels, the major radiation sensitive component, and for containment of the consequent activation problems.

Design studies for increasing the intensity to at least 10^{13} p.p.p. have begun. A separated orbit cyclotron could be used to obtain the required increase in injection energy. It is believed that the necessary increase in radiation resistance of vacuum vessels and other components could be obtained, leaving induced activity as the major obstacle. It is therefore of the greatest importance to develop a high efficiency extraction system thus minimising the necessity for special techniques to deal with active components.

In the meanwhile the utilisation efficiency of Nimrod would be greatly increased if a proposed new experimental area can be built soon.

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THE IMPROVED BEVATRON AND ITS PERFORMANCE AT HIGH INTENSITY *

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(Presented by W. W. Chupp)

A. HIGH INTENSITY

The present maximum beam accelerated to full energy at the Bevatron is 5.3×10^{12} protons per pulse, obtained with a 20 mA injected current. Although for normal operations the intensity is held at 2.5×10^{12}, studies of the machine behavior at peak intensities are continuing.

Fig. 1 shows the behavior of the accelerated beam versus injected beam soon after completion of the improvement program in 1963. Both the captured beam (1 ms after r.f. turn on), and to a larger degree the 6.2 BeV beam, show evidence of saturation with increasing injected current. For some time the accelerated beam appeared to be limited to 2.3×10^{12} protons/pulse. Improvements in the r.f. system, reduction of noise, and exploration of beam loading effects on electrode structures gave little or no help in increasing the limit. Some increase was obtained by adjustment of the lenses in the inflector system, but most of the improvement apparent in Fig. 1 followed adjustment of the magnetic field using the pole face windings. The field was changed in general to provide slightly greater vertical focusing as well as to compensate better for variations in the field near pole tip laminations.

* Work done under the auspices of the U.S. Atomic Energy Commission. The major Bevatron Improvement Program was carried out during the period 1962-65. See E. J. Lofgren, Proceedings of the International Conference on High Energy Accelerators, Dubna, 1963, p. 146.