The Indiana University 200 MeV cyclotron project *

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Presented by M. E. Rickey

ABSTRACT

A separated sector cyclotron facility is under construction at Indiana University. The ion source and potential drop pre-accelerator and the first cyclotron stage are being assembled at a temporary location. The design of the final cyclotron stage is nearing completion and its assembly will commence when the building, presently under construction, is occupied late in 1970. The completed accelerator will have variable energy over wide limits and will be capable of isochronous operation with both protons and a large number of heavy ions.

1. INTRODUCTION

The cyclotron project at Indiana University[1,2] underwent conceptual design in 1966 and a grant providing funding for the facility was awarded in June, 1968 by the National Science Foundation.

The floor-plan of the building to house the laboratory is shown in Fig. 1. The roof area of the building is to be approximately 65 000 ft^2 and the total usable floor space available will be in excess of 85 000 ft^2. The cost of the building, provided by the State of Indiana, is $3 500 000.

There will be three experimental rooms in the shielded area; two large rooms (50 ft × 50 ft and 75 ft × 75 ft) will have multiple beam paths. The third is intended for apparatus such as an on-line mass separator which requires close access to bombardment facilities. A large area is available for expansion of the experimental area using the initial beam handling equipment if it becomes necessary in the future.

The injector cyclotron will produce proton beams up to 15 MeV and will have an energy gain of 30. It will be a model of the final stage in many respects. Initial operation of this stage is planned to occur early in the spring of 1970. The area formerly occupied by the older Indiana University 45 in cyclotron, now dismantled, is being used as a temporary location.

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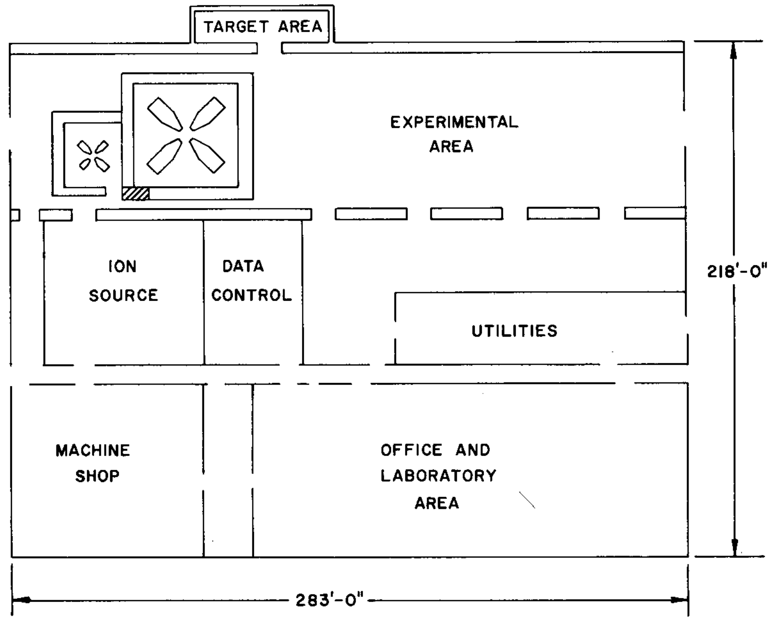

Fig. 1. Simplified layout of ground floor plan of accelerator building

2. CONTROL SYSTEM

A control computer has been installed and an extensive software and interface development is in progress. The equipment presently installed consists of a Scientific Data Systems Sigma II central processing unit with 16 384 16 bit words of core storage and an SDS Model 7929 digital input-output interface. Also installed are a 750 000 byte rapid access disc file, a magnetic tape unit and a Model 35 teletype keyboard unit with paper tape punch and reader. A multiplexed Hewlett-Packard Model 2401C digital voltmeter has been interfaced and a multiplexed Hewlett-Packard Model 5105A/5110B frequency synthesiser is being installed for multiple use. Uses in addition to an operating rf source will include nuclear resonance magnetic field measurements and a sampling measurement frequency source as described below.

In addition to conventional monitoring, adjustment, and logging functions, we hope to obtain computer assisted beam quality measurements using an emittance program originated at the National Accelerator Laboratory.[3] We hope also to develop a sampling measurement program which will provide a gain-bandwidth product sufficient to non-destructively measure such properties as phase history of the accelerated beam[4] (similar to measurements at ORIC) and output energy as a function of rf phase. These data will permit optimum isochronisation and extraction of relative phase and amplitude data for servo adjustments of the second harmonic flat-topping system being planned.

The computer will be used also for magnetic measurements, electrolytic tank data, and other measurement programs needed for design and assembly.

3. MAGNETIC FIELD

The present status of the magnetic field studies is as follows:
Early measurements were made with two small model 'C' magnets (pole tip areas of~125 cm^2). These magnets were made of SAE 2030 steel (a nickel-steel with 30 points carbon); the material was not given heat treatment in the course of fabrication. These magnets were made before the precise geometry of the cyclotron had become well defined and an angle of 50° was used rather than the 36° angle ultimately adopted. They were useful at low field strengths but gave only qualitative data concerning the magnetic circuit. Because of difficulties we encountered at the time in obtaining small quantities of low carbon steel and in reproducing its magnetic properties in a subsequent batch, a new technique was developed which we have found to be very useful.[5] The median plane solution of Laplace's equation with equipotential surfaces corresponding to pole tips of various shapes was found using an electric field measuring technique. It was possible to explore quickly various pole geometries, gaps, and coil distributions with very simple model construction techniques. These solutions corresponded to pole tips acting as magnetostatic equipotentials and it was possible to simulate also the consequences of various reluctance values for the flux returns. Using this apparatus, design criteria were evolved for the magnets of the first cyclotron stage. These have been acquired and are presently being assembled. In addition to the four sections needed for the cyclotron, a fifth magnet was purchased for future measurements and as a model magnet for the second cyclotron stage magnetic field. Measurements are currently under way with this facility.

With the cyclotron design which has evolved, the magnet gap need be no larger than that required for the beam aperture since the dees are to be located entirely in the valleys. It is possible, however, to use too narrow a gap from the standpoint of the magnetic circuit.

It is desirable that a large fraction (>90%) of the reluctance of the magnetic circuit be that of the gap at the highest planned flux density. If this is not the case, the valley field increases in relative strength, flutter is lost, and isochronous values of the radial gradient are badly altered.

The size of the gap and the location and dimensions of the main exciting coils determine the relaxation length of the azimuthal fringing field which in turn decreases the flutter below the hard-edge value. This is most prominent at the smallest radii.

The non-relativistic isochronous field is independent of radius in the hard edge approximation if the field edges lie on radial lines. This is slightly altered ($\Delta t/t \sim 10^{-4}$ at $r = 10g$ where r is the orbit radius and g the magnet gap) for our case, i.e. four-fold symmetry with 36° angular width magnets. The corresponding soft-edge condition is that the effective field boundary (EFB)[6] lie along a radial line. It is then important that the EFB not move appreciably as a function of field strength. This is accomplished in our case by the use of circular arcs of one gap radius along the radial magnet edges. The resulting EFB then is located approximately half gap out from the physical edge of the magnets.

These considerations, along with the dee system geometry and the magnetic properties of the iron, establish well defined criteria for the overall magnet design with respect to injection and extraction radii, magnet gap, and the flux return area relative to that of the pole tips.

A number of alternatives were considered in determining the trim coil configuration to be used. It became clear as studies progressed that 'hill' coils were much to be preferred over other types. The equilibrium orbit in the non-relativistic limit is well known in a magnetic field of this type. If the trim coils are shaped so that the radial gradient is normal to this orbit everywhere, the equilibrium orbit shape even at relativistic energies is unchanged.

This design has been chosen for our case. The coils are distributed so as to correspond to approximately equal numbers of orbits. The conductors are wide, thin strips of aluminium machined to the proper profiles and lying flat on the pole tip surfaces so that most of the tip area is covered by the trim coils. The resulting gradient profile is then near the isochronous value everywhere and variations of orbit phase and fluctuations of focusing frequencies are minimised.

The coils are to be hard anodised to provide insulation and will be mounted so that a double layer of anodised surface is present at all points

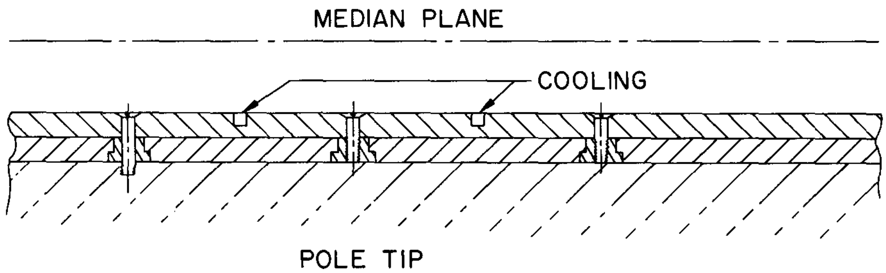

Fig. 2. Cross-sectional view showing a method of clamping the anodised trim coils with the cooling plate

of contact. Studies have shown this to be remarkably durable insulation capable of withstanding heavy direct beam bombardment without deterioration. It has good vacuum properties and is a good thermal conductor. Fig. 2 shows the approximate layout of the coils.

Distribution of the gradient windings along the entire radial extent of the magnets minimises power dissipation for a given coil thickness and in our case a maximum power density of $\sim$0·15 W/cm^3 permits indirect cooling of the aluminium conductors. The hill coil configuration leads to high current densities at the outer edges of the magnets ($\sim$10 times higher in our case). The long lengths of the conductors closing the current loops give corresponding large power dissipation in this part of the circuit; it is therefore desirable to use copper conductors away from the gaps. The indirect cooling of the gap conductors permits the use of mixed materials without introducing destructive electrolytic processes.

For operation with particles of low specific charge, low relativistic mass increases are encountered and dynamical constraints are relaxed. The main magnet coils can be operated at maximum power consistent with the installed cooling capacity and core saturation is relatively unimportant. For high specific charges and high β at extraction, much larger gradients are required and the maximum acceptable main coil excitation is considerably lower. We are presently planning to take advantage of these complementary power demands by using a single d.c. current source with separate controls for main coil and gradient coil power sources.

4. RADIO FREQUENCY SYSTEM

The two cyclotron stages will use 'dee' type accelerating structures with orbit phase widths of 40° between accelerating gap centrelines. The gap centrelines will be radial to avoid an excessive number of weakly-accelerating harmonics.

By the use of fourth and higher harmonics (other than the ninth and its multiples) continuous energy variation requires only a small range of radio frequencies. An rf such that 28 MHz$\leqslant f \leqslant$35 MHz is adequate. This bandwidth is comparable to that of television transmitters and an rf system without any tuning other than resonating the dees is planned. The resulting high value of and small variation in the pulse repetition rate is useful in many experimental set-ups. Use of harmonic numbers as high as 12 for lowest energies of ions of low charge-to-mass ratios is planned. Under these operating conditions less than 100 turns are required so that adequate isochronism should not be difficult to attain.

The small range of operating frequencies and the low dee capacity make it possible to tune the dee structures by dee capacity alone. This system has many advantages. On the lower harmonics where the highest energy gains are required and where the range of orbit parameters is greatest, operation with a constant number of orbits is planned. This requires highest voltages at the highest frequencies corresponding to the largest tuning capacitor gaps. In addition, the rf power requirements are nearly independent of frequency under these conditions. This is in marked contrast to conditions in most existing isochronous cyclotrons where the power for a given dee voltage increases rapidly with the rf; in addition to its consequences in the design of the rf system itself, the equilibrium temperature of the dee system is subject to variation because of this property and variations in the thermal expansion of the dee structure can be quite annoying. The fundamental frequency dee system is very simple structurally and no movable high current density connections are required.

The flat-topping system using supplementary second harmonic electrodes inside the fundamental dees[2] will be modelled on the small cyclotron stage to determine its practicality in the final stage. Orbit studies are in progress to determine the feasibility of operating the extraction magnet in a dispersive mode so that sampling measurements of the phase dependence of the output energy can be utilised as described in the control system section.

DISCUSSION

Speaker addressed: M. E. Rickey (Indiana University)

Question by G. Burton (M.R.C. London): Could Prof. Rickey give the beam current, emittances, and beam size of the proton beams at injection to the small cyclotron and state whether there is any bunching of the d.c. injector beam before injection?
Answer: The injected beam current is to be up to 10 μA with emittances of 10 mm mrad or less at 500 keV to both transverse dimensions. The optimum beam size for this emittance to match the cyclotron dynamics is an approximately circular cross-section of 1 mm diameter. No bunching prior to injection is to be used for light ion beams. The intensities available from a duoplasmatron ion source are more than are needed without klystron bunching.

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