# CURRENT STATUS OF THE INDIANA UNIVERSITY CYCLOTRON FACILITY+

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## ABSTRACT

Recent progress and the present status of the multi-stage Indiana University Cyclotron Facility are described. Some of the problems which have been encountered and their consequences and solutions will be discussed. Emphasis has been placed on work which has proceeded since the 1969 International Cyclotron Conference in Oxford.

## INTRODUCTION

The Indiana University Cyclotron Facility, first described in April, 1966[1], was partially funded by a grant from the National Science Foundation the following December. The complete grant for the cyclotron was awarded in June, 1968. The plans for the facility have been described in previous publications[2,3]. In February, 1968 disassembly of the earlier Indiana University cyclotron, which had been in operation since 1939, started. Shielding and all components of the 113 cm cyclotron were removed to provide an area for temporary installation of the present injector stage cyclotron and a prototype ion source prior to the completion of the new laboratory building. These components are presently in operation in the temporary location. It is planned to move them in October, 1972 to their permanent location in the accelerator building.

The building design evolved during 1968 and 1969. Acceptable bids were received in the summer of 1969 and construction started the following September.

## BUILDING

The design of the building has been discussed previously[3]. Construction was completed and the building was occupied in June, 1971.

Included in the building contract were a number of components intended primarily for the cyclotron. Among these were the cooling tower together with primary water circulation pumps for heat exchangers, filters, a water treatment system, and a refrigerated air conditioning system including widely adjustable air circulation and cooling distribution to the radiation area.

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The cyclotron machine shop has been installed and equipped with tools and materials and is presently operating at full capacity. The electronics shop has been completely equipped and is also in full use. The first part of the computing facility for control of experiments, a Datacraft 6024/1 system, has been installed in the data and control room. This computer will be used initially for magnet measurements and other cyclotron measuring systems requiring the handling of many data.

At the present time several of the 15 laboratory rooms on the ground level of the personnel area of the building are being used for offices. The remaining laboratories provide adequate space for present needs. One laboratory is being used as a drafting room. A target laboratory has been fully equipped and installed and is presently producing targets. The first of two chemistry laboratories is being equipped and the laboratory for solid state detector work is under development. When cyclotron construction is completed and operation starts, the upper level of the personnel area, presently unfinished, will be used for office space, making additional laboratories available for other purposes.

Each of the 15 laboratory rooms is equipped with a circuit breaker box and comprehensive power distribution, compressed air, gas, hot and cold water and a water drain. They are well illuminated and each room has independent temperature control. The floors were designed to permit easy installation of heavy loads and access for handling equipment was provided. Four of the rooms have hood exhausts installed with independent exhaust fans and ducts so that cross contamination can be avoided.

Also included on this level were a kitchen and a bedroom with separate bath facilities providing a rest area during long runs.

During the past year minor modifications and repairs have been completed and the building is well suited for present needs.

## ION SOURCE

The initial ion source consists of an Ortec model 350 duoplasmatron mounted vertically so that the extracted beam is directed downward. At present, this source is used with hydrogen gas only. Prior to entering the acceleration tube this beam passes through an einsel lens, a double focussing 90° wedge magnet, and an electrostatic quadrupole triplet similar to those in use in the Berkeley 88" cyclotron polarized proton source. Insulated alignment and diagnostic slits have been installed immediately before and immediately after the magnet. The magnet separates the three charge states ($H^+$,$H_2^+$,$H_3^+$) present in the hydrogen beam. The components preceeding the tube are mounted in a 2 meter cubical equipotential dome. Terminal ion source pumping is provided by a 5 cm diffusion pump backed by a small mechanical pump also mounted in the terminal. Power is provided by a 15 kVA 3 phase isolation transformer providing 120/208 volts insulated for operation up to 600 kV. Accelerating voltage is provided by a 20 mA, 525 kV maximum output power supply. This system is a single phase, 60 Hz voltage doubler with extensive filtering. The low potential end of the power supply is insulated for operation up to $\pm$ 30 kV from ground and a boost or buck regulator has been installed. The isolation transformer and high voltage power supply are in a single oil tank and require 2000 U.S. gallons of insulating oil. Power is fed to the terminal by 600 kV cables.

The accelerating tube is a 10 stage, 600 kV tube acquired commercially[4]. This tube uses ceramic insulators and aluminum electrodes having a 13 cm aperture. Deionized distilled water cooled by a ground potential heat exchanger provides cooling in the terminal and fixtures have been installed on each of the electrodes. The supply and return water columns in polyethylene tubing are used as voltage division resistors for the accelerating tube. A regulating signal for the terminal voltage is obtained from a resistive voltage divider.

It was found that beam losses in the ground end of the accelerating tube produced a gradual deterioration of the vacuum following turn-on and a rapidly increasing rate of X-ray production from the terminal occurred. These conditions became so severe with increasing terminal voltage that operation was impossible above 200 kV. This malfunction was corrected by using the last two stages of the tube in a back-biased mode to suppress backstreaming secondary electrons. This technique has been very effective and appropriate apparatus is being designed for installation of separate electrodes for this purpose in the ground end of the tube so that all of its high voltage sections will be available for acceleration. Presently the system operates at 300 kV without any noticable deterioration and a very low radiation level. Higher voltage operation probably will not be attempted at present due to restrictions imposed by the temporary location.

After leaving the accelerating tube, the beam passes through another larger vacuum pump station, another set of diagnostic slits, and a permanent magnet quadrupole doublet. It is planned in the near future to replace this quadrupole with an electrostatic doublet which has been developed using the 1968 design of Ovsyannikova et al.[5] We are considering electrostatic quadrupoles for focussing throughout the ion source area since focal lengths for reasonable voltage gradients comparable to those of magnetic quadrupoles can be attained easily for proton energies < 1 MeV and lower gradients are needed for heavy ion beams to be injected. These lenses are light, use little power, and require no cooling and this design has many desirable properties. Power supplies can be switched with little difficulty permitting an efficient, inexpensive system.

After passing through the quadrupole and additional diagnostic apparatus, the present beam is deflected 45° in the horizontal plane by a wedge magnet and passes through subsequent ion optical components so that an appropriate image can be formed near the entrance to the electrostatic inflector. Figure 1 shows the present system at its connection to the injector stage. In the present geometry the beam passes through a considerable region of cyclotron magnet fringing field of sufficient magnitude to produce considerable curvature and in which the transverse gradient has significant ion optical activity. A different beam path is being planned to reduce these effects and another inflector will be installed in the near future to inflect at a larger radius. The corresponding increase in inflection energy will increase the rigidity of the injected beam and further reduce fringe field effects. This energy boost will be provided by a rf driven single drift tube which will also provide appropriate beam bunches.

## INJECTOR STAGE

The major assembly of the injector stage cyclotron (which serves as a prototype of the final stage in many respects) was completed in 1971 and initial operation was achieved on May 18, 1972. Two minor but time-consuming vacuum problems and a rather persistent multipactoring problem caused considerable delay in its initial operation. In addition, the diversion of most of the staff to the accelerator building postponed some of the early developmental work on this stage. Operation with internal beam is becoming increasingly routine and much valuable experience and information are being obtained. The first extraction element will be installed soon.

Figure 2 shows a plan view of the median plane of this stage together with the instrumentation currently installed.

The main magnet is powered by a 2400 ampere, 100 kW transistor regulated power supply. Due to the narrow gaps of the magnets ($\sim 3$ cm between iron surfaces) and the magneto-motive force drop in flux return ($\sim 10\%$ at high fields) the coils have been connected so that each of the individual magnetic fields can be raised or lowered relative to the others by supplemental small, high compliance power supplies planned for installation.

The magnet center line probes shown in Figure 2 will contain nuclear magnetic resonance field sensors interfaced to the XDS Sigma 2 control computer. This equipment will permit rapid measurements of the absolute center line median plane magnetic fields on each of the magnets and the differential current adjustment capability will permit setting of the magnets to uniform field strength. At present only inexpensive Hall probe sensors are installed in these probes; hence, only relative fields can be measured and no information is available on the amplitudes of first and second harmonic components of the magnetic field. However, the behavior of the accelerated beam suggests that these produce only small effects at the field strengths used in recent months.

Figure 2 shows the locations of the gap spacers which determine the magnet gaps at the tips and backs of the magnets. A fifth magnet was obtained for modelling purposes in addition to the four installed in the cyclotron. This magnet was energized to $\sim$ one-half maximum excitation without spacers installed and a deflection of $\sim 1.5$ mm at the tip was observed. The gap spacers are important for maintaining the gap and for setting equal gaps of the independent magnetic circuits. Type 6061-T-6 aluminum has been used for spacer material in the injector cyclotron. These spacers also provide the mounting for the hard anodized aluminum gradient coils.

The use of hard anodizing for insulating the gradient coils has proven highly satisfactory. Each top and each bottom coil assembly is 6 mm thick, leaving a net gap of 1.8 cm, which comprises the vertical beam aperture for this cyclotron. Six coils are presently mounted on each of the trim coil panels: a central region coil permitting adjustment of the magnetic field in the present region of injection by a circuit closing around the tips of the magnets, and five coils of successively increasing radii which close around the outer edges of the magnets. The coils are formed of aluminum sheet with machined circular arcs comprising the inner and outer edges. The center of these arcs are not at the vertical axis of the cyclotron but, rather, are a function of radius. The coils are so designed that they conform approximately to the shape of hard edge equilibrium orbits and the radial extents of the coils correspond approximately to equal numbers of orbit paths in each set of coils under isochronous magnetic field conditions. The coils are connected in series. The geometry is such that a parabolic field rise would occur should all the coils have equal efficiencies. Each of the five outer sets of coils can be independently controlled in a manner similar to the differential control system described for the main magnets. This allows for adjustments for variations in these efficiencies and local variations in the magnetic fields.

## RF SYSTEM

As has been described in earlier publications, the rf system of this cyclotron operates over a relatively narrow band. (This has been reduced to 28 - 35 MHz.) Continuous variation of orbit frequency (and hence output energies) is achieved by shifts in the harmonic number of the orbit frequency of the rf. For the highest velocity output (maximum energy protons), the fourth harmonic of the orbit frequency is used. The orbit phase width of the dees is nearly independent of radius and is $40^\circ$ between gap centerlines; thus, the rf efficiency of the dee crossing in fourth harmonic operation is approximately 98% corresponding to $160^\circ$ rf phase width. The gap centerlines are radial so that the gap increases from 2 cm near the center to $\sim 10$ cm at maximum radius. Transit time effects for gap crossing are relatively small. The efficiency is comparable for fifth harmonic operation ($200^\circ$ rf phase width) and falls as the harmonic number is increased. The ninth harmonic corresponds to $360^\circ$ rf phase width and is therefore labile. The efficiency for $h = 10$ is comparable to that for $h = 8$. The decrease in efficiency with increasing h for $h < 9$ is compensated for by the smaller energy gain per turn required for the lower orbit frequencies; consequently, the radio frequency power requirements change relatively little for various beams being accelerated. The cyclotron, therefore, operates under approximately constant power conditions. The low dee capacities (primarily those of the accelerating gaps) have two desirable effects: (1) the power requirements are modest for reasonable Q values, and (2) tuning over the entire operating frequency range by varying dee capacity is possible without encountering sparking to the tuning capacitor plates.

The dees are made with sufficient room available in their interior regions for installation of supplementary second harmonic electrodes to be used in flat topping. Modelling indicates that this system will work without undue difficulties and installation in the injector stage is planned in the near future for evaluation.

The narrow frequency range used in this cyclotron permits the use of a wide band rf amplifier system so that the dee circuit is the only tuned element in the radio frequency system. Figure 3 shows a schematic of the radio frequency system presently installed. An earlier version of this system maintained constant bias on the final amplifier tube for Class $AB_1$ operation. The severe multipactoring problems mentioned earlier were encountered with this system to such an extent that operation was impossible. By the simple expedient of removing the constant bias components for the final stage and permitting the tube to operate under cathode bias conditions the impedance match under multipactoring conditions was improved permitting rapid outgassing and cleanup so that this problem is presently of little consequence. Four diffusion pumps using a Monsanto Chemical Company fluid, Santo-Vac 5 polyester fluid, maintain the vacuum for this cyclotron stage. It was learned that severe multipactoring was encountered in the prototype rf cavity at SIN in Zurich when diffusion pumps were used. In their case the trouble was eliminated by use of turbomolecular and ion pumps rather than diffusion pumps. In our system the multipactoring becomes less severe as the vacuum improves. Modest chilling of the traps for the diffusion pumps improved the base vacuum and it is planned to install a - 60°C, two-stage freon refrigerator for the baffles when the injector is moved to its permanent location.

The final amplifiers (EIMAC 4CW 25000's) are operated with their screens at dc as well as rf ground. The stored energy and reactive components in the plate circuit are so small that "crowbarring" is not necessary since under no circumstances is it possible for the plate to become negative with respect to the screen for a time sufficient to damage the screen. Fast overload trips in the holding circuits of the plate supply and screen supply contactors provide adequate fault protection. The low grid resistance and conservative operation of these tubes eliminate the necessity for neutralizing. The 90 ohm grid resistors constitute the dissipative elements of band pass filters and similar filters[7] are installed in the final stage plate circuits and at the driver inputs. The output capacity of the 800 watt driver amplifier is matched to the input capacity of the final amplifier by the autotransformer tap on the plate inductance of the driver.

The operating frequency of the system can be changed under full power. The frequency source is a General Radio Model 1165 frequency synthesizer having 100 Hz resolution and is interfaced to the Sigma 2 control computer as are the step motors which operate the tuning capacitors. A system presently under development will permit automatic tracking of the tuning and the rate of frequency change will be limited by the maximum speed of the tuning motors. Only a short while is needed to cover the entire frequency band.

The dee to dee capacity is vanishingly small and very little interaction is seen between the two dee systems. It is therefore necessary to control their relative phase. The optimum phase relationship is $\Delta\Phi_{RF} = 0^{\circ}$ for h even or $\Delta\Phi_{RF} = 180^{\circ}$ for h odd. A low level solid state, current controlled, constant amplitude phase shift network has been designed and installed. The relative phase of the two dees is determined by comparing the phases of an electrostatically shielded inductive pick-up from one dee resonator and a capacitive pick-up from the corresponding resonator for the opposite dee. These signals are $90^{\circ}$ out of phase for $\Delta\Phi_{RF} = 0^{\circ}$ or $180^{\circ}$. A phase error signal is generated using a Hewlett-Packard model 10514A mixer. When used as a phase detector with these inputs, this device has an output proportional to sin $\Delta\Phi_{RF}$ (i.e., the cosine of its input signals) and the system regulates to a phase detector output null giving phase regulation independent of rf amplitude. The dee voltage is sensed by symmetric capacitive pick-ups, each having a capacity to its dee of $\sim 10^{-14}$ farad. The rf signal is converted to dc at each pick-up by a hot carrier diode used in a peak detection circuit. The diodes used for this purpose have peak reverse voltages of > 80 volts. The rectifiers are operated at a 50 volt dc output level for 50 kV peak dee voltage and the rectified output goes to a 10:1 dc attenuator. The nonlinearity of the diode at levels up to 1 volt (this occurs for a dee voltage of 1 kV or less) then becomes inconsequential. The systems are calibrated so that the linear regions of their outputs extrapolate to the origin eliminating zero offsets in the operating range. Each voltage divider output signal drives an amplifier follower. The operational amplifier outputs are averaged to obtain a signal proportional to dee voltage, independent of small motions of the dees due to coolant flow, vibrations, etc. Two pick-ups are used for each dee.

The averaged output of each of the two dee voltmeter systems controls an additional 10514A mixer used in the current controlled attenuator mode. Without regulation there are a few percent of 360 Hz ripple on the dee voltage. When the dee voltage feedback loop is closed the ripple is not detectable. The short term regulation is estimated to be $\sim 1$ part in $10^{4}$.

At present the phase control feedback loop is not closed for operation. The inflected beam is presently too near the tips of the magnets during the first few orbits for isochronism. Apparently as a means of compensating for this, highest beam intensities occur at phases other than the optimum ones. Even without feedback, the relative phase is very stable after warming. The planned modifications of the injection system described earlier will largely compensate for this.

It is desirable to form beam bunches prior to injection into the first cyclotron stage. A klystron bunching system is planned for installation with low average intensity sources. For protons and other light ions klystron bunching is neither necessary nor desirable. It is planned to prepare beam bursts in these instances by installing the second rf harmonic (56 - 70 MHz) drift tube of appropriate length referred to earlier. This will be operated at 75 - 100 kV peak voltage and will be installed in the beam tube prior to the first horizontal bending magnet at a waist of the beam. The energy modulation, together with the dispersion of the bending magnet, will provide beam bursts at a coherent repetition rate. The radio frequency source for this system will be derived from the frequency synthesizer and passes through another channel of the current controlled phase shifter. This will permit phase compensation for the transit time between this equipment and the cyclotron. The increased energy produced by this buncher will permit injection at a larger radius as noted earlier.

## FINAL STAGE CYCLOTRON

The final stage cyclotron magnets have been completed and delivered. Two sets of coils are on hand and the remaining ones will be completed in the next two or three months. One magnet has been assembled and operated at full current for preliminary measurements. It is shown in Figure 4.

All parts for the magnet supports are on hand. Each magnet will be mounted on three 150 ton jacks which are, in turn, mounted on two orthogonal sets of Tychoway roller bearings for horizontal adjustment. The tips of the jacks support the magnet through tapered roller bearings to avoid transmitting torque to the supports while the system is being repositioned.

The magnet cooling system has been completed and installed in its permanent location. The main magnet power supply is presently in operation and its regulator is being adjusted and improved. The current sensing for the regulator is derived from a current transductor[7] rather than a shunt. This device is extremely accurate, has a low temperature coefficient and provides high level output (10 volts maximum) giving good noise immunity. A set of prototype gradient coils is being prepared for installation for magnet measurements. All vacuum system components[8] are on hand and the cryopumps are presently being tested.

Included in the magnet fabrication were four magnet vacuum chambers. These were made of annealed magnet steel plate to provide field clamp action giving a harder edge. A preliminary modelling was conducted on a fifth sector of the injector stage but due to differences in materials and in the magnetic circuits these results were only of qualitative value. The aperture of these boxes, presently two gaps (15 cm), will be increased to $\sim 6$ gaps and extended radially at the inner and outer edges. This will reduce the field clamping near the edge of the magnet somewhat but will lead to considerably lower flux densities in the clamp circuit and reduce perturbations of the gap field. It will also provide additional space needed for trim coil leads and for the rf liners near the median plane. This modification will move the effective field boundaries of the magnet outward somewhat. This, in turn, will increase the radial separation of the magnets slightly. The Valley vacuum chambers and the dee systems have undergone preliminary design but their precise dimensions are strongly dependent on the location of the effective field boundary. It will be necessary to wait until the second magnet has been assembled with the modified vacuum chamber before the dimensions of these components can be determined precisely.

Since the magnet components must be carefully cleaned and degreased before assembly, and since they will be assembled several months prior to completion of the vacuum chamber, it was decided that all steel components which will be in the vacuum will be plated with $\sim$ .05 mm of nickel to minimize rusting. Commercial plating was considered but was decided against because it was impossible to locate a commercial plating firm with vats of sufficient size to take the larger components anywhere in the vicinity. Even if such a facility had been located, the freight costs and the added risks due to the extra handling would have encouraged adoption of the techniques finally selected. After considerable developmental work, a satisfactory brush plating technique has been developed. All plating will be completed in the next two months.

The dee structure for the final stage is presently being studied using a low power half scale model. The amplifier system used in the injector stage will be adapted to the final stage using 100 kW vapor cooled tetrodes. A prototype final amplifier has been assembled.

## CONCLUSION

Many other systems are under study and development and installation of power distribution equipment, cooling equipment, etc. is under way. Assembly is proceeding at a satisfactory rate and it is hoped that construction can be essentially complete by the end of 1973. All members of the group are actively engaged in the development of the many systems needed for satisfactory operation of the complete system.

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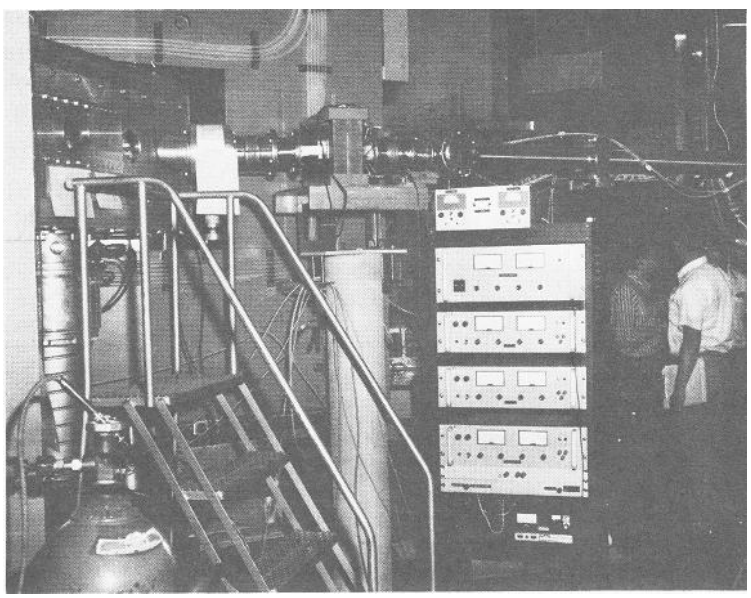

Fig. 1. Connection of the ion source system to the injector stage cyclotron. The controls are presently located in the cyclotron vault to permit more detailed studies of the injected beam properties.

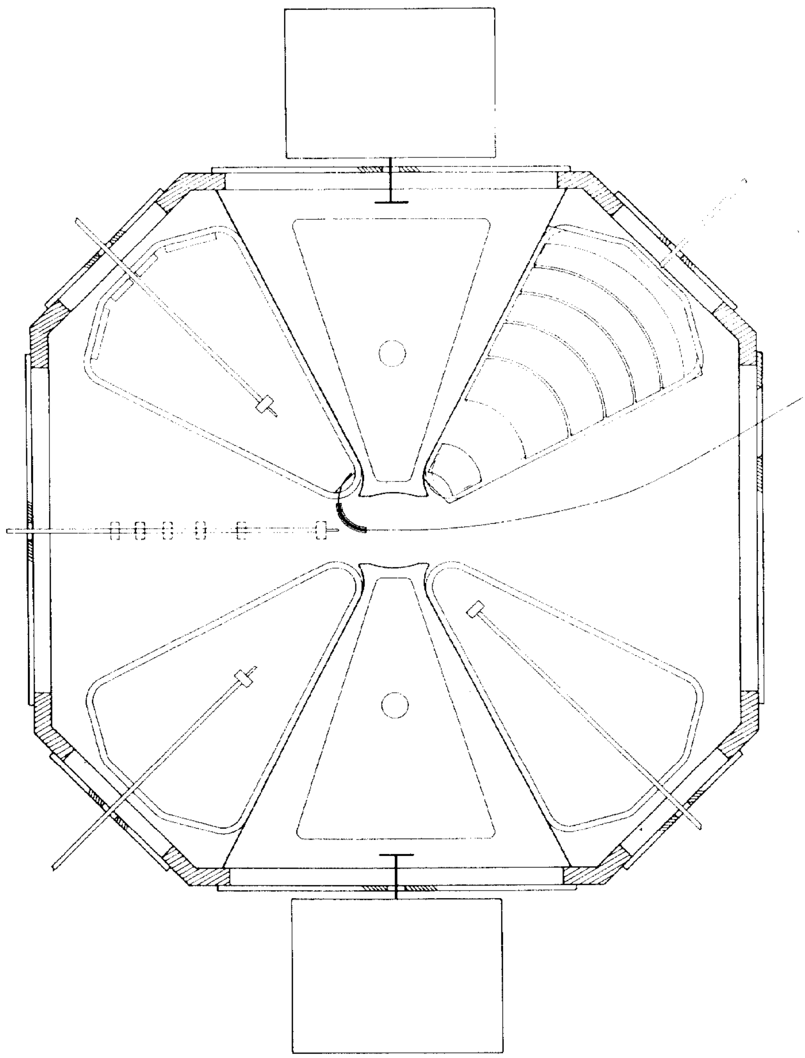

Fig. 2. View of the median plane of the injector stage cyclotron. The structures in the top and bottom center are the dee structures and driver amplifiers. The top left probe has an insulated tip for detection of the injected beam. The bottom left probe tip has an insulated tip for studying the extracted beam trajectory. The probes in the magnets to the right contain only field scanning equipment. For clarity, the layout of the trim coils is shown in the upper right magnet only. A removable probe also enters from the left. The dashed boxes indicate locations of capacitive pick-ups for orbit phase measurements. The number and locations of these can be changed easily.

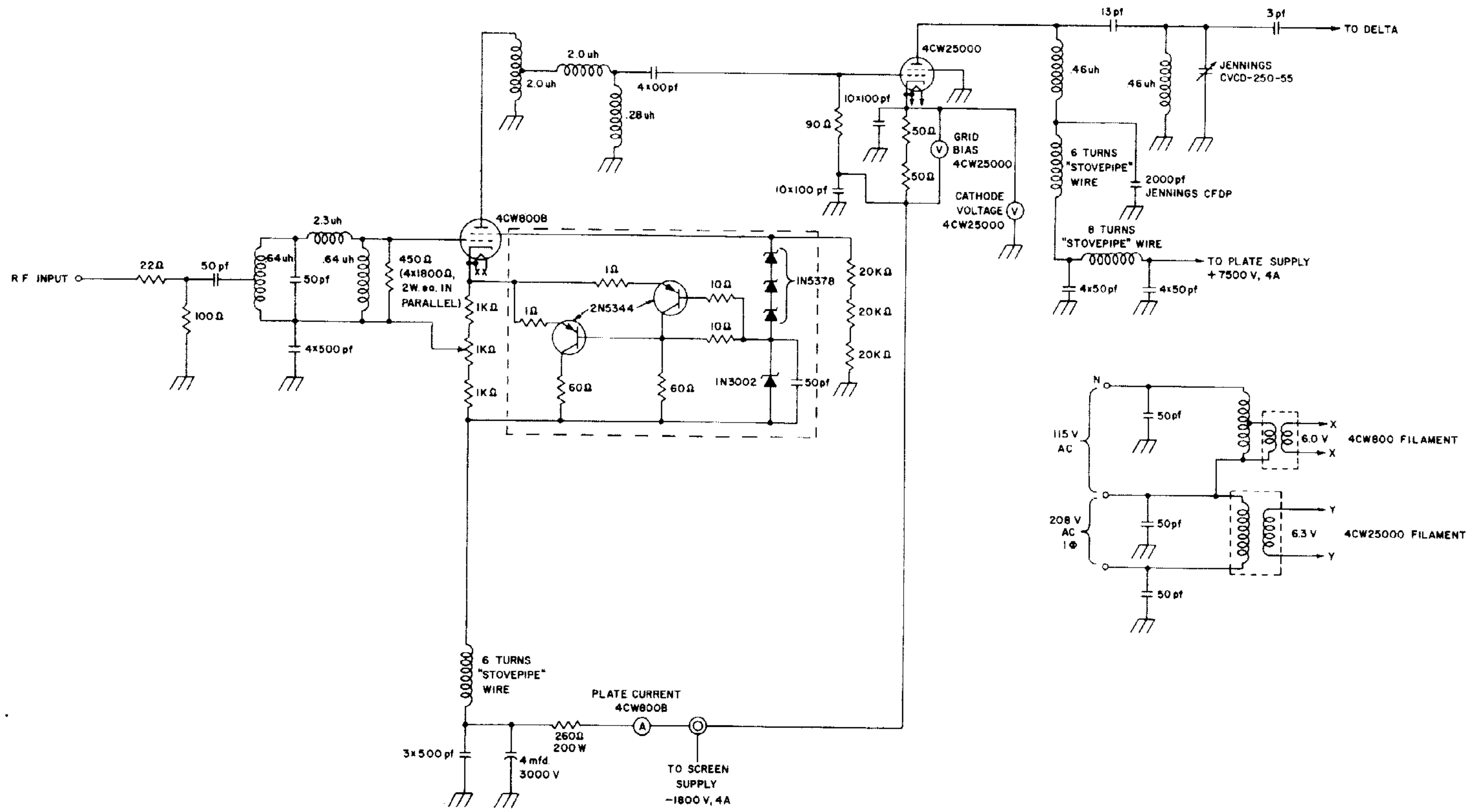


Fig. 3. Present components installed in the cyclotron vault providing dee ("delta") rf drive. A power of ten watts maximum from a 50 ohm source is sufficient to drive the dees to maximum voltage. The 90 Ω and two 50 Ω resistors shown in the final stage are commercial low reactance resistors modified for water cooling to increase their dissipation.

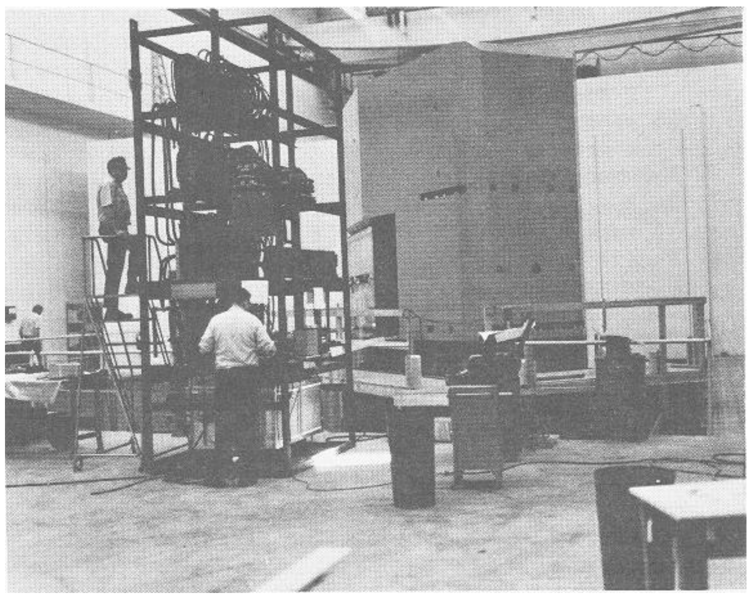

Fig. 4. This is the first assembled final stage magnet. The system being prepared in the foreground is the main magnet power supply. The pole tips of the magnet are away from the camera. The coils are mounted but are not visible due to the magnet vacuum chamber.

DISCUSSION

RICHARDSON: I understand the phenomenon that you were concerned with (multipactoring), but the cure isn't quite clear to me. You said that you biased the cathode--is that the power amplifier tube? Would you say just a bit more about that?

RICKEY: The cure isn't clear to us, either. The main thing about it is that it worked in our particular instance. If one looks at the operating curve of the 4CW25000 (the power amplifier) it curves very drastically. It doesn't have a linear grid control function. We had been operating at a fixed bias, -375V, and under those circumstances 200V peak on the grid was adequate to drive it to full output without multipactoring, but it would not drive very strongly during multipactoring. We really weren't concerned about putting in excess drive. Another way of looking at it is the plate resistance was relatively high, under fixed bias circumstances. Now when the dee is multipactoring, of course, it represents a completely different load from the shunt resistance when it is running in the proper way. Our conjecture is that by changing the bias point, which with the changes to cathode bias in effect changed from -375V to about -250V, we were up where we got a much higher drive to the tube for this particular period, and the plate resistance came down, probably making a better impedance match between the dee and the amplifier while it was in the multipactoring mode. And so the difference was that it coupled in a great deal more power. It took the pressure way up, no damage, no sparking or anything like that. Just the pressure went way up, and after a couple of moments, we turned it off, letting the pressure recover. That is what we think has happened on it. Turn it on and there is dee voltage.

HENDRY: On the multipactoring problem again, is it entirely impractical to bias your dee system?

RICKEY: No, it is not. That's one of the things we considered. However, it is not easy. It could be done; one could put in mica. The loss tangent on mica is entirely acceptable, and it would be well cooled. It would be quite easy to put on a kilovolt or so, which would be adequate to wipe out the multipactoring. Under the circumstances, it would have been very difficult to install. We are working in a restricted place. We don't have good rigging right now. We can't take the hardware apart easily. Later on when we have the use of the crane in the new building, we will be able to do so. We were considering biasing the system, but fortunately, we don't have to now. That was a very real possibility, and it <u>is</u> practical.

NEED: I would like to clarify my understanding of the gradient coils. Those are single strips, then, of anodized aluminum and you edge-feed them?

RICKEY: Right. There is an equipotential along each edge so that there is not current feeding at a point but rather it is distributed over the entire edge.

AULD: The injection from your ion source into the first cyclotron gave me the impression of trying to aim a fire or water hose in a wind. Can you give us any of your experience in the problems of injecting through the valley field of the cyclotron?

RICKEY: That is one of the things that will be changed in the next go-round. We have a system designed now which will move over closer to the centre-line. There are two consequences of going along roughly parallel to the pole-tip. One is the curvature in the field due to the dipole contribution. But then the transverse gradient has considerable focal properties also. Bob Pollock calculated a focal length of 2 ft or so. It was quite short, and indeed it's remarkable that we can get in, under the present circumstances, with that big a perturbation and working, so to speak, with it on the end of a long pole. Two things that will improve that a great deal are firstly, going up in injection energy, which we will need to do to get out of this very bad tip region; that will also increase the rigidity of the beam. And secondly, as I say, we have the new path which goes much closer to the centre, and the field is smaller and the gradient is much smaller.

So this system is by no means optimum now, it is just a first start on it. The nice thing about it, the encouraging thing, is that it works, and works surprisingly well, I might say, for a first attempt. We are pleased that it works so well. Of course, we know a great many things in retrospect that we didn't know at the time we were proceeding on it. We have one other big advantage. We have a good opportunity of reviewing what we do because we will take the machine completely apart and rebuild it, and we can leave out those things that we don't want. At least, most of them--we can't leave out the fringing field, unfortunately.