DESIGN AND PERFORMANCE OF A COMPACT H$^-$ CYCLOTRON

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Abstract.- Six negative hydrogen ion cyclotrons using an internal ion source have been constructed and are currently being installed. Factory tests on these accelerators have shown that 200μA of external beam is readily available, and maximum external currents in excess of 250 μA have been achieved. The cyclotron and its associated beam transport is operated through a bus-oriented computer system. The principal applications of this cyclotron are medical isotope production and fast neutron production for radio-therapy.

1. Introduction.- The charged particle beam available for bombarding targets external to a sector - focused cyclotron is usually limited to about 2000 watts by the power dissipated by the septum. This limit is substantially raised if negative ions are accelerated and extracted by removing electrons by stripping. Negative hydrogen ions have been accelerated in a number of sector - focused cyclotrons.[1,2,3,4] The beam currents usually have been limited to 100 microamperes or less, and to achieve the higher currents, axial injection systems have been used.[3,4]

The CP-42 Cyclotron is a negative hydrogen ion cyclotron with internal ion source, designed to produce 200 microamperes of external proton beam at energies up to 42 MeV. The principal applications of this cyclotron are medical isotope production and fast neutron production for radiotherapy.

Extensive tests of this cyclotron system have demonstrated that its design goals have been exceeded over prolonged periods of operation

2. General Description.- The design details of the major systems of the CP-42 Cyclotron will be discussed in the following separate sections. The main features of this accelerator are given in Table 1.

Figure 1 shows the general layout of the CP-42 cyclotron. Two 90° dees and the half-wave resonant transmission line are supported by shielded alumina insulators. The rf oscillator and the coupling loops are positioned on the top of the upper vacuum plate which is fastened to the upper half of the magnet structure. This structure can be lifted up by a hydraulic drive, permitting easy access to all components in the median plane. The vacuum tank is made of 25 mm thick stainless steel plate. A number of port openings are provided for insertion of various components and for multiple beam exits. At each corner of the lower vacuum plate is mounted a 10-inch diffusion pump with associated cold trap.

The ion source and radial beam probe are mounted in a conventional manner. The variable energy extraction system consists of a precision extraction foil positioning mechanism, a motor-driven magnetic channel and a combination magnet. The path of 11 MeV and 42 MeV beams are schematically shown. Three fixed energy beams can also be extracted through the dee stem to the pre-determined exit ports and beam handling systems.

3. Computer Control System.- The cyclotron control system has been designed to allow the operation of the cyclotron and its beamlines with minimal manual control. Presently, control is achieved via a simple interactive keyboard, where the operator is largely responsible for tuning the critical variables. The control system is currently being developed to reduce the amount of operator involvement by gradually introducing more "intelligence" through feedback control software, so that ultimately the task of obtaining external beam will be reduced

TABLE 1. Major Features of CP-42 Cyclotron

Particle Accelerated	H$^-$
Beam Energy	11 - 42 MeV
Beam Current (external)	200μA
Energy Resolution (FWHM) at Max. Energy	1%
External Beam Emittance	30 mm- mr
Operating Frequency (fixed)	26.8 MHz
Accelerating Mode	Fundamental
Pole Diameter	120 cm
Max. Extraction Radius	53 cm
H$^-$ Ion Source	Internal, PIG
Vacuum and Pumping Speed	6×10^{-6} torr, H_2
	1.2×10^4 liter/sec, H_2
Method of Extraction	Charge Exchange
Nominal Extraction Efficiency	100%
Beam Exit	Multiple
Control	Computer, TCC Bus

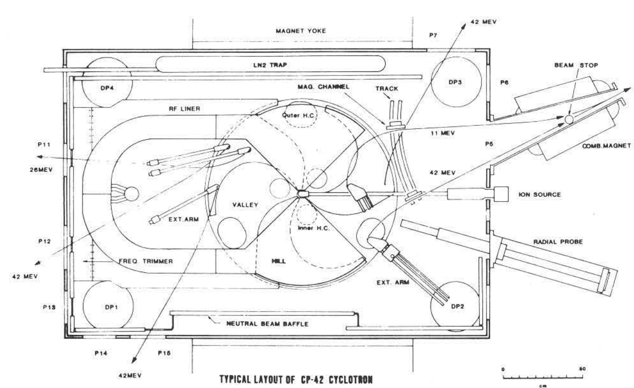

Fig. 1 : General Layout of CP-42 Cyclotron

to a few keyboard commands giving specifications of the beam particle, the energy, and the extraction port.

The control system uses a Digital Equipment Corporation PDP-11/03 microcomputer with a dual floppy disc unit and specialized keyboard terminal, which communicates with the cyclotron subsystems on a TCC-designed bus. Following a study of such systems as CAMAC and IEEE 488, it was decided to design our own TCC bus mainly to overcome noise immunity problems not adequately coped with on the commercial busses. The TCC bus was modelled on that of the DEC Q-bus, to facilitate the operation of the TCC bus from the PDP-11/03 computer. Each cyclotron subsystem appears to the computer simply as one or more registers which may be accessed via the TCC bus. Hence the main magnet, for example, may be controlled on the TCC bus in a similar manner to, say, the printer on the Q-bus.

The computer communicates with the registers located in modules purpose-built for the particular cyclotron subsystems. Up to five control modules are housed in a crate which also contains the module power supplies and the bus interface. The interface, besides providing the decoding logic to allow the control modules to be addressed, isolates the modules electrically from the bus.

The cyclotron control software has been implemented under DEC's RT-11 operating system in the MACRO-11 and C programming languages. A multitasking system architecture was chosen and is supported by a priority scheduler of TCC design that works in cooperation with RT-11. Tasks communicate through system common tables. The entire control software package resides with the operating system on one floppy diskette, leaving the other drive available for logging and record-keeping.

The multitasking design permits the various tasks to be written as though they were independent subroutines. Separate tasks get data from the TCC bus, control output to DACs and motors through the TCC bus, update console CRT and meter displays, respond to operator commands, and communicate with customer computers or other equipment. The tasks are scheduled according to assigned priorities and individual nominal frequencies that range between 3 and 30 Hz. Operator actions such as pressing a button or turning a knob are logged directly by an interrupt handler, setting flags that will be acted upon later by the appropriate tasks.

In addition to the common tables used for intertask communication, configuration tables describe the cyclotron - - what equipment is available, calibrations, and so on. With this table-driven design, it is particularly easy to produce and modify customized configurations.

The command language uses mnemonic abbreviations typed by the operator to control cyclotron parameters, to reassign the functions of the console buttons and knobs, and to control the operating and diagnostic displays. In addition, some debugging commands are available to aid in program maintenance.

4. Radio Frequency Characteristics.- Following previous work at TCC[5)] the RF equipment in the vacuum tank is composed of two 90^{o} dees coupled by a half wave resonant transmission line. Dee-to-ground clearance is maximized by copper plating the hills and pole tip plates, which eliminates the dee liner and decreases dee capacity. The resonant transmission line connecting the dees is a simple U-shaped structure which is water-cooled to dissipate up to four watts per square centimeter. The dees and the resonant transmission line are mostly open on the median plane to allow for the passage of neutral and extracted beams. The entire dee-transmission line structure is isolated from ground by suitably shielded alumina insulators which have proved reliable over extended operating periods. Voltage bias and cooling-water are supplied to the structure at the low voltage node at the center of the transmission line. The operating dee voltage is 35kV peak producing an energy gain per turn just over 100 keV. The RF power required at this level is 45kW.

The RF system is powered by a grounded grid oscillator which employs a triode with 60 kW anode dissipation (ML 6696A). The oscillator is coupled to the dee structure with two short resonant transmission lines[6]. The cathode line, foreshortened by the cathode capacitor, operates in a half wave mode while the anode line, foreshortened by the anode capacitor, operates in a quarter wave mode. For combined resonator copper losses and beam power requirements of 55 kW the D.C. input to the oscillator is about 80kW. The oscillator is powered by a series-regulated 10kV, 10 amp anode power supply. This supply provides dee voltage adjustment, dee voltage regulation and fast crowbar protection.

The operating frequency of the cyclotron is determined by the frequency of the dee structure. This frequency is controlled against a crystal reference using a small inductive panel in the high current portion of the transmission line liner. The frequency is held within $\pm$75 Hz of an operating frequency of 26.8MHz.

5. Magnetic Characteristics.- The CP-42 employs a three-sector AVF cyclotron magnet. The pole diameter is 120 cm, the valley gap is 12 cm, the minimum gap is 5 cm, and the maximum spiral is 64^{o}. The maximum average magnetic field is 1.85T at the average 42 MeV extraction radius of 51.3 cm. Beam loss due to Lorentz stripping is negligible at the magnetic field levels used in the CP-42. Harmonic coils located at average radii of 13 and 49 cm are used for centering the beam.

The magnet is powered by a 500 ampere 250 volt transistor-regulated power supply. The stability of this supply is one part in 100,000. The harmonic coils are powered by bypolar supplies which control the first harmonic independently along two orthogonal cartesian axes. To correct for slight variations in steel composition and treating, the field in each magnet is measured to an accuracy of about 1 part in 10,000, and the hill shims are trimmed to provide a good isochronous field.

6. Ion Production.- The ion source follows the basic design[7)] used in all TCC cyclotrons. The anode of the ion source is patterned after the work of Ehlers[8)], and has been optimized for H^- output and gas efficiency. The position of the source can be adjusted in four dimensions, while the arc current is supplied by a continuously adjustable current regulated power supply. At 35 kV RF dee voltage, 300 μA of H^- can be accelerated routinely to 15 cm radius with about 6 SCCM gas flow and 1.5 amperes of arc current. Optimal current up to 500 μA at 15 cm has been obtained with four amperes of arc current. For 200 μA extraction, only 240 μA at 15 cm is required. After a one hundred hour test of 200 μA beam extraction, the cathodes showed little sputtering upon inspection. The life time of a pair of cathodes would be at least 200 hours.

7. Extraction.- Several types of foil extractors are being designed and installed. Three fixed-energy extraction arms of the same type can be positioned to take beam at different energies through ports 11,12,13,14 or 15 as shown in Fig. 1. Each arm can be raised to the median plane and adjusted within a few millimeters for the exit position and direction, as well as to compensate for the effects of foil movement. Horizontal slits at each exit port are used for beam tuning.

One arm with an extended position drive extracts variable energy beams through port 5, and pre-determined energy beams through ports 6 and 7. This arm uses a four-foil cartridge for long periods of uninterrupted operation. The motor-driven magnetic channel is positioned according to the corresponding extraction point and beam path which is determined by an extraction code. A beam stop at the converging center of the combination magnet detects extracted beam current and guides the operator to fine-tune the extraction foil along the equilibrium orbit of a given energy. After all conditions are satisfied within the cyclotron, the beam stop is retracted, and the combination magnet guides the extracted beam to a conventional beam handling system.

8. Vacuum System.- The gas stripping loss of H^- ions is proportional to the electron density present in the accelerating region. This implies upper limits for partial pressures of tank gases to keep stripping losses below acceptable levels. For the CP-42 the partial pressure of water is kept below 1×10^{-6} torr, and that of hydrogen below 6×10^{-6} torr, insuring total gas stripping loss of less than 25 per cent for 42 MeV beams. To maintain the total effective hydrogen pressure of 1×10^{-5} torr at the maximum ion source hydrogen flow rate, 0.1 torr l/sec, requires a net pumping speed of 10,000 l/sec. The conductance from the central region to a pumping assembly was optimized using a TCC-developed Monte Carlo computer simulation, to a value C_1 = 10,000 l/sec. The conductance of the pumping stack value is C_2 = 55,000 l/sec, and of the chilled trap/water pump, C_3 = 15,700 l/sec. Using a 10-inch vapor diffusion pump with a hydrogen pumping speed of 7,000 l/sec nets a pumping speed of 3,080 l/sec per pump stack. The CP-42 uses four such stacks for a total of 12,300 l/sec (verified by measurements), which exceeds the maximum requirement above.

9. Neutral Beam.- For full power operation (200 µA at 42 MeV) about 15 percent of the negative hydrogen ions are neutralized. The resulting beam loss is approximately an exponential function of radius. The resulting neutral hydrogen atoms follow straight trajectories, stopping at the first surface they encounter. The dees and dee steems are almost completely open on the median plane to avoid intercepting this beam. To the fullest extent possible the neutral beam is stopped on water-cooled aluminum neutral beam baffles which line the vacuum tank. The principal isotope generated is ^{24}Na (15 hours half-life). If it is necessary to work in the vacuum tank, the baffle can be removed in about five minutes. The resulting activity problem in and around the cyclotron is of the same order as that encountered with the positive ion CS-30, which is a lower current and energy machine.

10. Performance and Operating Experience.- We have tested our cyclotron at full beam current and at full energy. Extraction of 42 MeV beam has been confirmed, and the energy spread has been within ± 0.5 percent. The extraction of 200 µA external beam has also become a simple routine. Due to the limitation of laboratory space, the beam emittance has not been measured for every available beam exit. For the 42 MeV beam extracted through port 12 (see Fig.1), the measured horizontal phase space was 4 mm-mr, while the vertical was 34±5 mm-mr. However, there is strong evidence of the slit-scattering which may overcloud the true phase space value when the Grunder emittance grid is used for 42 MeV protons.

The interactive computer control has been working well except for a few occasional noise-generated problems. The system has shown itself to fulfil the main design criterion of ease of communication. The modular approach to both hardware and software has provided the flexibility needed successfully to build and operate several different cyclotron configurations.

The ion source routinely produces sufficient H^- ions effortlessly. The 200 µA external beam can be brought up entirely by ion source arc current control without any other retuning, including adjusting the position of the ion source, indicating that no space-charge problem is encountered at the rated beam intensity. The pyrolytic graphite foils used for extraction last about 60 hours for 200 µA operation. The life-time was not limited by material evaporation but by radiation damage. It is believed that the lattice structure of the graphite crystal is altered by recoil displacement and by impurity created from nuclear reactions.

The designed stability of the major cyclotron parameters, such as RF frequency (1 in 10^5), magnet current (1 in 10^5) and RF dee voltage (1 in 10^4) have been achieved. It would have no meaning to display a section of strip-chart recording of the 200 µA external beam current as a function of time, since except for occasional crowbar event, the record was just a straight line of constant amplitude. However, due to the 8 kW beam power loading on the RF system, frequency stabilization was found to be essential.

An endurance test for 100 hours uninterrupted extraction of 200 µA at about 40 MeV was carried out on the cyclotron to be installed at TRIUMF. The target was a water-cooled copper plate enclosed in a stainless steel Faraday cage which is coupled directly to port 7 of the cyclotron. This arrangement prevents us from making a residual activity survey on the cyclotron alone. Two pairs of horizontal slits and one vertical slit were used to guide the tuning and to monitor the change of beam behavior. A four-foil carousel capable of being remotely indexed was used. Target currents and foil currents were monitored and strip-chart recorded side by side. It is of interest to mention that these two current signals are an exact image of each other.

Except for initial tuning at the beginning of the test, the entire operation was uneventful. All operating parameters were practically unchanged. Schweickert and his associates from Karlsruhe participated in the initial tuning at the beginning of the test, while J. Bergerjon from TRIUMF witnessed the conclusion of the program.

Conclusion.- The feasibility of using high power negative hydrogen ion cyclotrons for medical applications has been demonstrated. The simple and reliable characteristics of this type of accelerator are particularly well-suited for radioisotope production and for fast neutron production for radiotherapy. Future plans include the acceleration of higher energy-higher intensity D^- and H^- beams.

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