THE IMPLEMENTATION OF A NEW RF SYSTEM FOR THE UNIVERSITY OF MANITOBA CYCLOTRON

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Introduction

One of the major aspects of the present University of Manitoba upgrading project was the construction and implementation of a new RF accelerating system. The new system includes two dees, each tuned with a separate rectangular coaxial tuning stub (Fig. 1). The two dees are coupled to the RF supplies inductively and are driven independently by two 25 kW RF amplifiers (Fig. 2). Dee voltage of 40 kV is obtained with only 10 kW of input power per side. Exceptional phase and amplitude stability have been achieved.

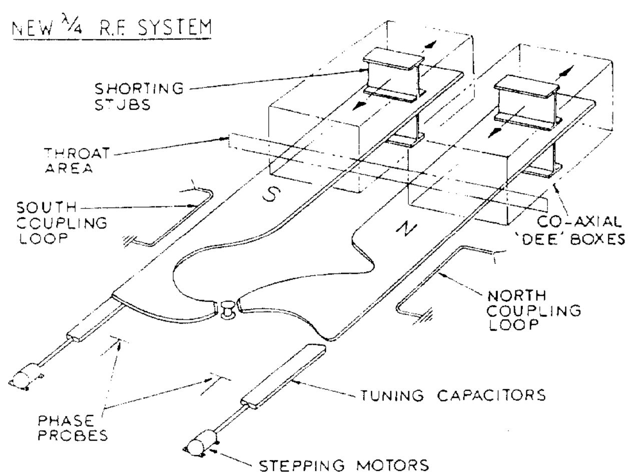

Figure 1. New dee system.

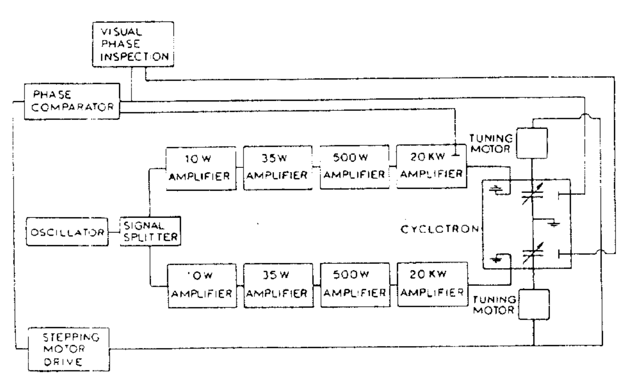

Figure 2. Block diagram of complete system (new).

In order to test the feasibility of this design, a half-scale model was constructed and tested. The operation of the full scale system was different from the half-scale model because of the existence of the magnetic field and unanticipated design problems. The difficulties encountered, and their resolution in the course of bringing the RF system to successful operation, will be discussed.

The RF System - Old and New

Two of the major objectives of the recently completed University of Manitoba cyclotron upgrading project were to improve the beam intensity for both proton and deuteron beams and to improve the extraction efficiency and energy resolution for both polarized and unpolarized deuteron beams. In order to achieve these objectives, it was necessary to design a new dee and dee-tip system with the associated RF power requirements.

There are many basic differences in the design of the old dee/RF system and the new system. The old dee/RF system was a one-half wavelength design in which the dee stems were electrically connected by a shorting bar. RF power was coupled inductively to one dee, from a 25 kW final amplifier. Operation of the dees in phase was impossible. Deuteron acceleration was limited to operation of the dees at one-half the normal frequency and a correspondingly lower magnetic field setting and injection voltage.

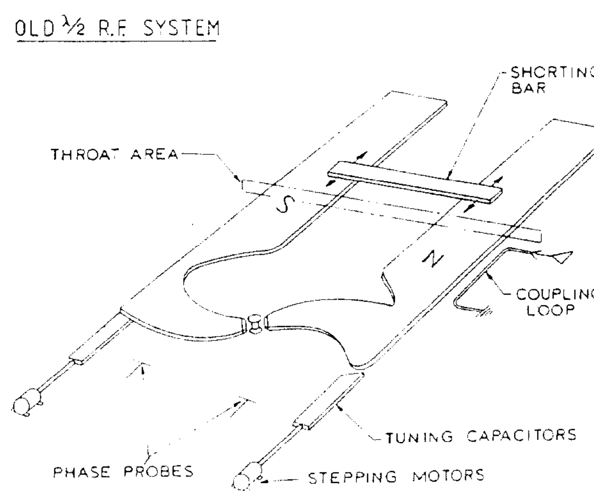

Figure 3. Old dee system.

The new dee/RF system is designed to accelerate deuterons with the dees in phase in the second harmonic mode. This allows the injection of deuterons at a much higher energy, increases the energy gain per turn by a factor of almost four, and allows for the possibility of single turn extraction for these particles at lower energies.

The old half wavelength dees have been replaced by new independently tunable quarter wavelength dee structure. The dees are electrically isolated and

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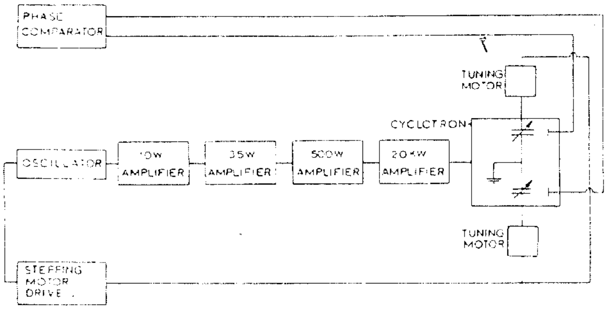

Figure 4. Old RF system.

separate 25 kW RF finals supply the power inductively to each dee. Tuning is by means of coaxial shorting stubs on each dee stem, which is the inner conductor of a low impedance rectangular coaxial line. These coaxial shorts, or shorting stubs, are connected to two blocking capacitors of 6000 pF each. The capacitors are required to isolate the dees from ground so that a DC bias voltage can be applied to eliminate multipactoring. The shorting stubs can be moved (with the RF on) along the length of the dee thereby tuning the dees for the required mode of operation. Switching from the push-push mode of acceleration (dees in phase) to the push-pull mode (dees 180° out of phase) is therefore quite easy.

The RF signal is supplied by a commercial frequency synthesizer, then split by a small transformer feeding two chains of amplifiers which supply the cathodes of the grounded grid finals with up to 400 Watts of RF power. Identical final amplifiers use Eimac 3CW 20,000 A7 tubes which can supply 20 kW of RF power with 400 Watts of drive. The high power output of the finals is fed to the inductive coupling loops by two 1 5/8 inch diameter, 50 ohm semirigid coaxial cables. The design voltage of between 40 kV and 41 kV dee to ground is easily achieved with 10 kW of RF input power per side. Reflected power is about 100 Watts to 200 Watts at operating levels. The Phase of the dee voltage, measured with a Rhode and Schwarz vector voltmeter, varies by only 0.2° after a short warm up period. Fine phase control is accomplished by two trim capacitors consisting of small Cu plates which are remotely positioned under the dees by a control signal picked off the vector voltmeter.

Implementation of the New RF System

The initial design of the new RF system was based on a 1/2 scale model. Test results from this model implied that the inclusion of the isolating capacitors in the coaxial dee stems would not affect tuning characteristics. It was also expected that RF leakage past the sliding shorts would be negligible. Some problems with the sliding shorts were anticipated. To minimize these, a set of pneumatically pressurized shorting stubs with knife contacts were designed to eliminate possible burning of the finger stock contacts.

The first attempts to inject RF into the machine were unproductive because of the vastly different behaviour of the machine compared to the 1/2 scale model. The problems were traced to the shorting stubs. To improve the short circuit capability between the top and bottom contact bars, heavy copper braid was soft soldered between them. The contacts were cleaned, polished and a higher clamping pressure applied with the result that it was possible to tune the dees to the desired frequency.

When 400 Watts of drive was fed to the two coupling loops, it was discovered that strong magnetic coupling between the dee stems, a high standing wave on the feed lines, and incorrect phase matching resulted in a very poor voltage gain. Because of the design of the dee stems, nothing could be done about the magnetic coupling. The phase of the amplifiers was matched by terminating the high power feed lines into 50 ohm loads. All phase shifts after this adjustment were considered to be directly attributed to the machine parameters.

With the feed lines connected to the machine, the relative phase could be adjusted by varying the distance of the coupling loops to the dees and by independent tuning of the dee circuits. After several unsuccessful attempts of tuning using these two methods, it was discovered that the impedance of the machine did not match the impedance of the transmission lines. This was attributed to a last minute change in the design of the coupling loops. In order to fit the coupling loops into the machine, they had to be shortened by 30%. A small water cooled choke was inserted between the feed line and each coupling loop in order to effectively lengthen the coupling loops thereby matching impedances. The standing wave ratio improved to better than 1.1 to 1 and the RF/dee system could now be tuned.

After a few days of outgassing under low to moderate power, up to 5 kW of power could be fed in per side. Higher power levels were still not possible however, as the vacuum did not improve beyond

$8 * 10^{-6}$ Torr. Analysis of the residual gasses showed that there was a small water leak. A series of newly installed stainless steel fittings, complete with stainless steel ferrules, did not seal properly to the copper water lines inside the vacuum chamber. The copper tubing flowed under repeated tightening of the fittings. It turned out that stainless steel fittings should never have been used for copper tubing. They were replaced by brass fittings (of the same design).

Outgassing for several days with RF power on enabled operation at high power levels (14 kW per side) for short periods of time. X-ray measurements of the Bremstrahlung at the dee tips indicated a dee to ground potential of 27 kV with 7 kW power in per side. The voltage gain was still not adequate and a further doubling in input power produced a dee to ground voltage of only 36 kV, 4 kV shy of the design voltage. These power levels could be maintained for only half an hour at a time; overheating of a water cooled copper liner, overheated shorting stubs and drive mechanism, and binding of the drive mechanism so that tuning of the cyclotron was impossible were only some of the problems that surfaced. In fact, the soft solder joints on the shorting stubs had melted and nylon screws which held down the isolating capacitors were damaged by RF. Furthermore, the tubing which supplied the air pressure to the shorting stubs meled resulting in air entering the cyclotron.

Extensive modifications were required to get the machine back into working order. Firstly, it was realized that there was indeed a high level of RF power in the coaxial deeboxes. As a result the drive mechanism for the shorting stubs, which extended into this intense RF field, was shortened to cut down the RF heating of the drive rods. Also, the nylon screws were replaced by a Teflon clamp which was fixed to the dee box by brass screws. These screws were subsequently changed to stainless steel screws as the zinc in the brass sputtered away leaving a conductive coating on any insulators in their proximity. The pneumatic shorting stubs were replaced by solid blocks of copper with finger stock soft soldered to the top and bottom. The copper liner was replaced by heavier gauge copper to improve thermal conductivity.

Operation of the RF was now possible at 10 kW in per side "continously". Unfortunately after eight hours of running, a cooling water line drew an arc from one of the grounded liner skirts in the vicinity of one of the dees. By the time the water was shut off, over one inch of cooling water had accumulated in the vacuum chamber. All cracks and crevices in the machine were filled with water. The inside of the cyclotron was dismantled, resulting in a delay of one month.

After assembly, the machine was outgassed with an input power of 14 kW per side. The pressure was now less than $3 * 10^{-6}$ Torr during operation with dee voltages nearing 39 kV. Beam was injected and accelerated for the first time on December 13, 1984 at 1418 h. Several days of operating experience indicated that RF related heating of the INVAR blocks on the magnet pole faces, heating of the vacuum RF chamber to over 60 C, and a low Q of the machine were still problems to be resolved.

Investigation into the INVAR heating problem indicated that the high RF fields in the vicinity of the dees penetrated through any opening in the cooled dee liners, heating INVAR blocks which were not even visible. This problem was eliminated by carefully covering the openings with copper sheets. The excessive heating of the vacuum chamber took place close to where the dee boxes joined the dee liners. It was therefore concluded that improved cooling in this area together with an improved electrical contact between the mainliner and the ground plane of dee boxes should decrease the losses. Also, two (5 cm diameter) capacitative pickup probes were removed from the vicinity of the dee tips to eliminate loading. Cooling of the shorting stubs also proved necessary as repeated heating and cooling of the soft solder joints on the finger stock was crystalizing the solder.

A pronounced improvement in the Q of the machine and a resulting improvement in the voltage gain was observed after these changes. Power levels of only 10 kW per side are required to operate the dees at 40 kV. This represents a total decrease of 4 kW of power into the machine to achieve the same voltage. The phase and voltage stability improved dramatically as well. Phase drifts between dees is now less than 0.2° with no automatic control.

A micro-computer control system, based on the Atari 800XL is being built. The ADC inputs on the joy stick ports will be used as an input for the error signals from the vector voltmeter and standing wave meters. A BASIC program will control the trim capacitors based on the information from these ports.

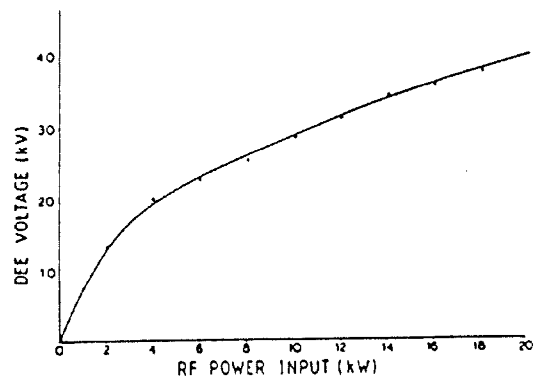

Figure 5. Characteristics of RF power versus dee voltage (dee to ground).

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