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A MOPA RF SYSTEM FOR THE INS 176 cm SF CYCLOTRON

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Abstract.- A master oscillator and power amplifier (MOPA) rf system has been constructed at the INS SF cyclotron replacing a self-excited oscillator system. The new system works well in a frequency range of 7.35 - 22.5 MHz and can produce a dee voltage of 85 kV at 20 MHz. The dee voltage is regulated within 0.02 % (p-p)/p by using a wideband feedback amplifier. Automatic tuning systems for phase and impedance, and an automatic pre-tuning system operate well without adjusting manually their operating parameters at any frequency. The entire system is controllable by a personal computer.

1. Introduction.- The INS 176 cm SF cyclotron has been in operation since 1974. The original rf system [1] was a self-excited oscillator with a triode 9T71A(Toshiba). This system supplied an rf power to the dee only in the frequency range of 7.35-17.5 MHz. There has been a constant demand for extending the frequency up to 22.5 MHz. Such a limit was mainly caused by the reason [2] that a plate load impedance became too low to be matched with the triode above 17.5 MHz. In order to overcome this difficulty, a flexible and powerful MOPA system, which is widely tunable in the plate load impedance, was proposed and its construction was decided.

Parameters of the power amplifier were determined by the experiences on operation of the cyclotron. The maximum dee voltage was chosen to be 85 kV, since severe sparks on the dee electrode were experienced above 85 kV. The maximum power consumption of the main resonator was estimated to be 140 kW at 85 kV and 20 MHz in the case of proton acceleration of the maximum energy 48 MeV.

Prior to the construction and installation of the new rf system, two kinds of tests were made. A full-scale model of the plate tank was connected to the cyclotron and electrical characteristics of the combined system were measured. The parameters of the plate tank were determined from these data. A test-bench, in which all the components except the cyclotron resonator and the plate power supply were assembled, was prepared for trouble-shooting. A test was made by feeding a small amount of rf power to a load resistor and it was checked that the entire system worked well in a frequency range of 7-23 MHz.

Installation of the new rf system in the cyclotron began in mid-September 1980 and was completed in mid-February 1981. During this period, the cyclotron was shut down. In late-February, the cyclotron started to accelerate the ion beam again.

2. MOPA system.- The schematic diagram of the new system is shown in Fig.1. The system is divided into six major components; an Anritsu MG440B frequency synthesizer(MO), two current-controlled attenuators, a bandpass filter, a Marconi H1000-02 wideband driver amplifier(DA), a power divider and an RCA 4648 final power amplifier(PA). Four feedback loops are incorporated into this system; a dee voltage regulation loop, a phase regulation loop, a tuning loop of the plate load impedance and an automatic pre-tuning loop. The system is also equipped with many protection circuitries for transient phenomena and control circuitries. The entire system is controlled by a personal computer and a programmable logic controller.

3. Power amplifier.- The power amplifier [3,4,5] at the Oak Ridge Isochronous Cyclotron has two features, which are applicable to our PA. One is the use of the plate tank [3,4], which provides large flexibility for matching the power tube to the main resonator. The other is the use of the all-pass network for grid rf circuit [5], which eliminates most circuit tuning in the frequency range of 7-23 MHz. It permits the use of a wideband and untuned driver chain. Since these features are advantageous to our PA, a new power amplifier has been designed following the ORIC's power amplifier.

The mechanical structure of the PA is almost the same as the ORIC's PA, which has been described in references 3 and 4. The load impedance of the power tube is widely variable by adjusting the resonant frequency of the plate tank. It is then possible to eliminate the adjustment of the coupling capacitance between the PA and the cyclotron resonator.

The all-pass network of the PA grid rf circuit for matching and terminating works well. The voltage standing wave ratio is less than 1.2 in our frequency range.

The low-impedance "screen bypass" capacitor is very important for a good PA stability. The screen bypass is disc capacitors which are assembled as a double-decker sandwich of Kapton film(3 mil in thickness). Its capacitance is 36000 pF and is sufficient for a dee voltage stability less than 0.02 % (p-p)/p.

To protect the power tube from abnormal operation, the plate and the screen power supplies are equipped with crowbar circuits, which have a fast response of 1 μs and work well.

Table 1 shows some of the operating parameters, together with those when the PA is operated at a maximum rf output in the case of 85 kV and 20 MHz. An rf power of 110 kW is less than the estimated one of 140 kW.

Plate dc voltage	13.5 kV
Screen dc voltage	1190 V
Grid bias	-105 V
Filament dc current	1550 A
Plate load impedance	700 Ω
Dee rf voltage	85 kV peak
Plate rf voltage	12.5 kV peak
Grid rf voltage	100 V peak
Plate dc current	11 A
Screen dc current	0.5 A
Output power	110 kW
Efficiency	74 %

Table 1 Some operating parameters for the 4648 PA.

4. Automatic phase regulation.- The rf signals from the pick-up electrodes at the grid, plate and dee are fed to intermediate-frequency(IF) amplifiers and are converted into 455 kHz IF signals by means of the superheterodyne technique. The phase difference between two IF signals is then measured by a digital phase meter commercially available, Wiltron 351. The phase difference between signals from the grid and plate is used as a tuning error signal in the phase regulation loop.

In order to maintain the phase regulation in pulse rf excitation, a combiner system has been developed. The digital phase meter produces a false and non-zero signal when its input vanishes. To avoid null input of the phase meter in the case of pulse rf excitation, the combiner adds a continuous but low level 455 kHz signal to an IF signal from the pick-up electrode. The resultant signal is then fed to the phase meter.

Two trimming capacitors, small and large, are automatically driven in the phase regulation loop. The small one is directly driven by the tuning error signal from the phase meter. The large one is driven by an error signal which is proportional to the deviation of the position of the small capacitor from a standard value.

5. Automatic impedance tuning.- Four vacuum variable capacitors of the plate tank are automatically driven and the resonant frequency of the plate tank is tuned to keep the plate load impedance constant. The dee and plate rf swings are compared in dc level and the difference between them is used as the error signal of this loop. This system, which is very convenient to set the impedance at a given value, was largely used in finding an operating condition during the initial tuning of the new system but is not used for the usual operation.

6. Dee voltage regulation.- The bandwidth of the feedback loop for dee voltage regulation is an important factor to be carefully considered, especially when one wants to stabilize the dee voltage even for pulse rf excitation and pulse-arc operation of the ion source. In these cases, the pulse repetition rate and pulse length are typically of the order of milliseconds. The bandwidth required for the feedback loop may be more than 10 kHz. The bandwidth of the main resonator due to the finite Q-value, however, varies from 500 Hz at low frequencies to 5 kHz at high frequencies.

The feedback amplifier consists of the following two amplifiers connected in parallel. One has a narrow bandwidth of 600 Hz and the other a wide bandwidth of 30 kHz. The difference signal between the dee voltage and an analog reference is fed to both amplifiers. Output signals from them are summed and a resultant signal is used as the error signal for the dee voltage regulation. The gain of the amplifiers is adjusted to avoid self-oscillation in the closed loop. The overall gain of this loop becomes unity at 4 kHz. The bandwidth obtained in our dee voltage regulation loop seems to be an optimum compromise between the requirement and the variable bandwidth of the resonator. It can be realized without adjustment of the parameters of the loop for the whole operating frequency in spite of the wide variation of the Q-value.

Typical stability of the dee voltage is 0.02 % peak to peak noise levels per peak rf voltage.

7. Automatic pre-tuning system.- The resonant frequency of the cyclotron resonator should be matched at least roughly with the operation frequency before an rf power is fed to the cyclotron. The pre-tuning is carried out automatically in our case by using the synthesizer as a sweep oscillator. While the plate and screen voltages are not applied yet, the control grid is excited by an rf power. The signal excites the cyclotron resonator weakly through the stray capacitance between the grid and plate of the power tube. The resonance signal of the dee voltage is processed to generate a tuning error signal, which is proportional to a difference between the resonant frequency and the central frequency of the sweep. The large trimming capacitor is automatically tuned. After this pre-tuning, the phase regulation in rf power excitation of the cyclotron can start stably.

8. Control.- The control system embodies all the circuitry required to perform the following functions in four operation modes by using a personal computer.
(1) Preset.- The six motor-driven elements, shown in Fig.1 as a symbol M, are automatically positioned to the calculated value prior to the rf excitation.
(2) Pre-tuning.- An automatic pre-tuning, described in the preceding section, is carried out in this mode.
(3) Baking.- This operation mode performs baking out the cyclotron resonator by means of pulse rf excitation without the dee voltage regulation.
(4) Power drive.- Three operation types, normal drive, pulse drive and drive without regulation of the dee voltage, are possible in this mode.

When severe sparks are detected in the cyclotron during CW operation of the system, the rf excitation is switched from CW to pulsing. When sparks vanish during the pulsing, a CW operation starts automatically again.

In the transient period of the rf excitation when the entire system is not in a stationary state, it is difficult to regulate the dee voltage severely because a slight error in the dee voltage might cause overdriving of the system. To avoid this, the following sequential controls are used; a pulsing and a CW operation without the dee voltage regulation, a gentle regulation and a severe regulation of the dee voltage.

In the "power drive" mode, the large trimming capacitor is automatically positioned to the predetermined value after the rf excitation is stopped. This control compensates the possible mis-tuning due to the thermal deformation of the dee electrode when the rf excitation starts again.

9. Summary.- As all the circuitry has wide dynamic ranges of the frequency and level, no manual adjustment of their operating parameters is necessary at any frequency and dee voltage. This simplifies the system control and makes a computer control possible. Operation of the MOPA rf system is thus easier than our old self-excited rf system.

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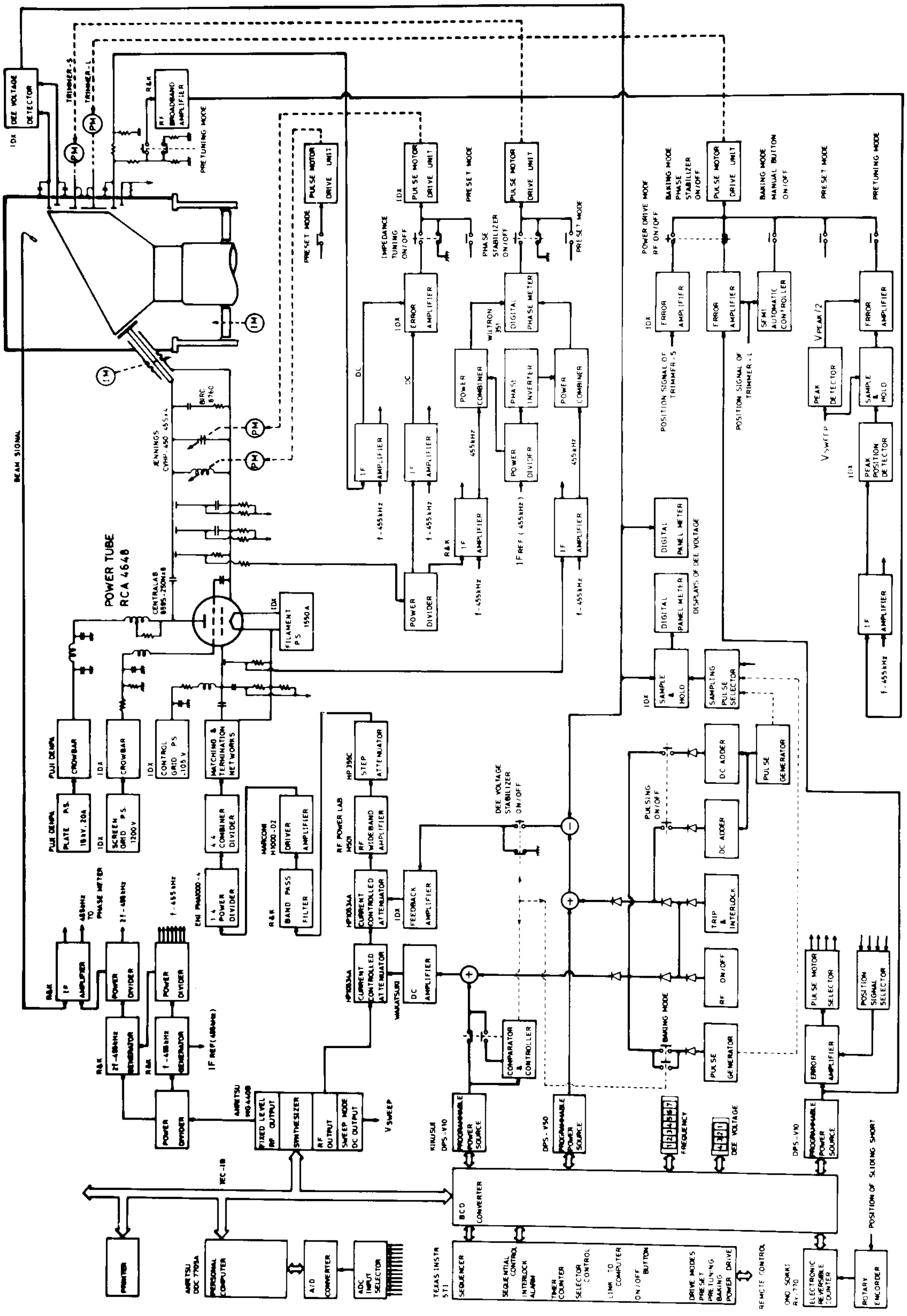

Fig. 1 Schematic diagram of the MOPA rf system