SPECIALITIES IN THE RADIO-FREQUENCY SYSTEM OF K500 SUPERCONDUCTING CYCLOTRON AT VECC

Sumit Som, RF Division
Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Kolkata-700 064
E-mail: ssom@vecc.gov.in

Abstract

The three-phase RF system of Superconducting cyclotron has been developed in the frequency range of 9 to 27 MHz with amplitude and phase stability achieved better than 10 ppm and $\pm 0.5^{o}$ respectively. Around 80kW of RF power at the highest frequency is fed from tetrode-based high power RF amplifier to each of the three cavities to develop the peak accelerating voltage of 100 kV at each dee. A PC-based stepper motor controlled precise movement system has been developed for coarse tuning the cavities at different frequencies and also a PC-PLC-based hydraulically driven closed-loop trimmer control system has been developed for fine tuning the cavity which gets detuned due to its thermal expansion while operating with high RF power. Precision control of trimmer (~20μm) is essential to achieve the Dee voltage stability better than 10 ppm. and also to minimize the RF power to maintain it. The trimmer control logic has been substantially modified and now the Phase difference between Dee-in and Dee-pick-off signals and the reflected power signals (from cavity) together act in closed loop for fine tuning of the cavity. It mitigates the problem of nonlinear behaviour of friction and dead band of the valve. Substantial improvement is observed with introduction of this technique in the trimmer control loop and effect of jittering is completely eradicated. The closed loop PID control determines the final positioning of the trimmer in each power level and achieved the required voltage stability. Finally, the closed-loop amplitude and phase regulators have been developed to achieve the specified amplitude and phase stability. They are based on RF modulator and I&Q modulation technique respectively.

INTRODUCTION

The Radio-frequency system [1] of k500 Superconducting cyclotron (as shown in Fig.1) is a master-oscillator-power-amplifier (MOPA) system, where the rf signal from a highly stable (better than 0.1ppm) frequency source is fed to a wideband three-phase (3ϕ) generator and it provides three rf signals of same frequency (with 120^{o} phase difference between each other). Each of these three rf signals passes through various amplifier stages and then coupled to each of the three resonant cavities by coupling capacitors (coupler).

The RF system consists of three half-wave coaxial cavity (operating in TEM mode) placed vertically 120 degree apart. Each half-wave cavity (as shown in Fig.2) has two quarter-wave ($\lambda/4$) cylindrical parts tied together at the centre and symmetrically placed about the median plane while each $\lambda/4$ part consists of a short-circuited coaxial transmission line (dee-stem) terminated by the accelerating electrode (Dee). The coarse frequency tuning is done by the movement of the sliding short. The fine tuning of the frequency is achieved by a hydraulically driven trimmer capacitor. The drive power from the amplifier is fed to the cavity at the dee by a hydraulically driven coupler. Major component details of the quarter-wave resonant cavity have been discussed below.

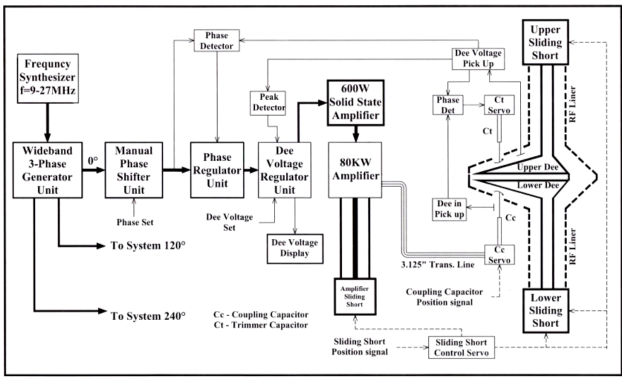

Fig.1. Block diagram of RF system for k500 Superconducting cyclotron

Dee Stem:

The dee-stem consists of two portions, the fixed and the variable length coaxial transmission line. The movable portion helps to tune the frequency in the range 9 MHz to 27 MHz. The movable portion is in air and it is a uniform line of hexagonal outer conductor and circular inner conductor. However, the fixed portion, in vacuum, is a tapered line. Both the coaxial lines are made of copper. The use of tapered line makes it possible to reduce the total power consumption of the cavity, limit the current carried by the sliding short and minimize the possible mode interference problems. The tapering impedance and its profile are given below.

$$Z_0(d) = 37. - 3.77 \times 10^{-6} \times d^{3.5} \qquad (1)$$

[Where, $Z_0(d)$= characteristic impedance at a distance "d" from the dee. $Z_0(0)$=37 ohm =starting characteristic impedance, Taper constant = 3.77 x 10^{-6}, Shape constant = 3.5, Tapering radius= R = 2.375 exp (1.47 x 10^{-6} x $d^{3.5}$); where, Starting radius = R(0) = 2.375 inch].

It is evident from the plot (as shown in Fig.3) that $3\lambda/4$-mode frequencies do not cross over 3rd harmonic

($3f_o$) and 5th harmonic ($5f_o$) modes, if the said tapering profile is followed. Otherwise, it may cross over $3f_o$ and $5f_o$ mode frequencies and thus resulting in higher order mode interference, which is undesirable.

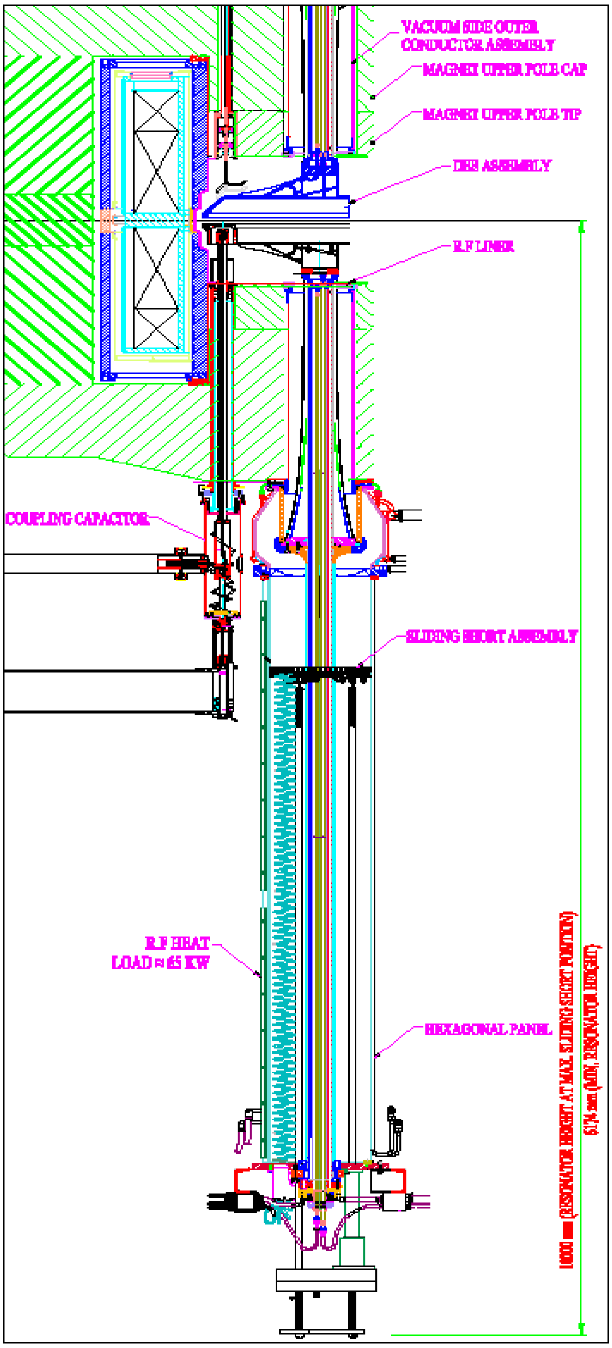

Fig.2. Coaxial RF cavity including dee and dee-stem

The RF performance of the cavity has been analyzed [2] by using SUPERFISH code and the plot of Quality factor (Q_o), Power dissipation and Short Ckt. Length vs. fundamental frequency is shown in Fig.4. Q-value is maximum at around 18 MHz. The cavity power dissipation increases and short ckt. Length decreases as the frequency is increased. The coaxial line (in air) consists of hexagonal outer conductor (each side of hexagon 201.65±0.05 mm.) and circular inner conductor (with O.D. 58.42±0.05 mm.).

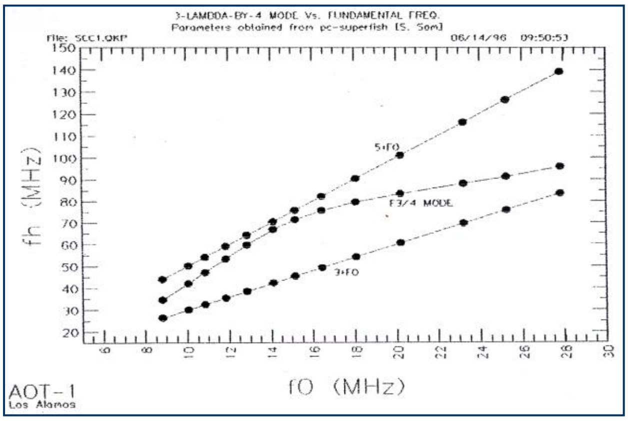

Fig.3. plot of 3λ/4-mode vs. fundamental mode

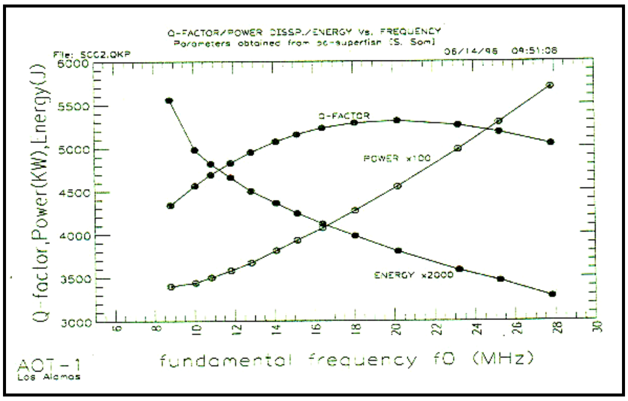

Fig.4. Plot of Q,Power dissipation,short ckt. Length vs. f_o

Sliding short:

The sliding short plate is electrically connected to the outer and inner conductors of coaxial line by Be-Cu contact finger (as shown in Fig.5) with sliver-graphite (99%Ag +1%C) contact ball at the tip. The coarse frequency tuning of the cavity is done by up-down movement (approx. 4370 mm.) of the sliding short. A PC-based stepper motor controlled system has been developed for the said movement. In this system, p315x stepper motor driver/indexer is used to control the stepper motor. The sliding short movement control of the 3 amplifier cavities and 6 main dee cavities for tuning at different frequencies can be done from a computer located in the main RF control room through LAN. As this indexers have RS232 interface, RS232/LAN converter ie network enabler (NE-4110s) is used. User interface Program is developed in JAVA and this communicates with the indexer through LAN. Network enabler and the PC, where the user interface program is running, both are connected to LAN. Client server architecture is followed here. Both client and Server program is developed in Java. Server is communicating directly to indexer through LAN and client programs which are running in browser communicate with the server for sending command to or receiving data from the indexer. MySQL database system is created for storing positional data of the stepper motor controlled sliding short movement system for different frequencies.

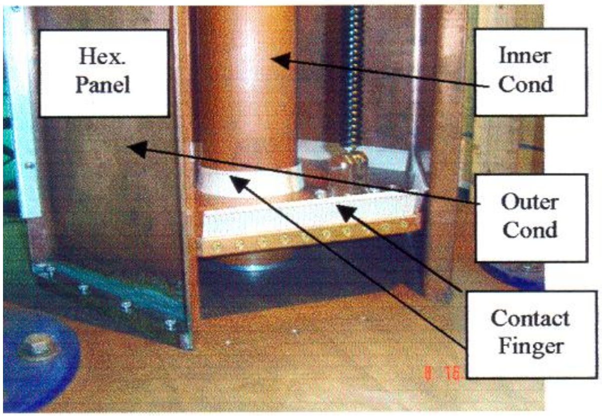

Fig.5. Sliding short contact fingers for the cavity

Dee:

The spiral shaped Dee (as shown in Fig.6) has been splitted into two halves (upper and lower dees) and symmetrical about the median plane. It is located at the valley of the superconducting magnet. They are galvanically connected to produce symmetrical electric field. Dee-to-dee coupling is eliminated by proper shielding to make each dee acting as a separate capacitance w.r.t. liner (ground).

Fig.6. Assembly of lower dees

Coupler:

The drive power from final power amplifier is fed to the cavity by a hydraulically driven vacuum variable coupling capacitor (Coupler) through 3-1/8 inch rigid coaxial transmission line with characteristic impedance of 50Ω. The coaxial type C_c is varied from 2 to 8 pF (approx.) to match the impedance of the transmission line to the shunt impedance of the cavity.

Trimmer:

The fine frequency tuning (±0.3%) of the cavity is accomplished by a hydraulically driven (schematic as shown in Fig.7) trimmer capacitor formed between the plate inserted from top and upper half of the dee. The criterion for fine tuning the cavity is that the phase difference across the coupler is 90^o.

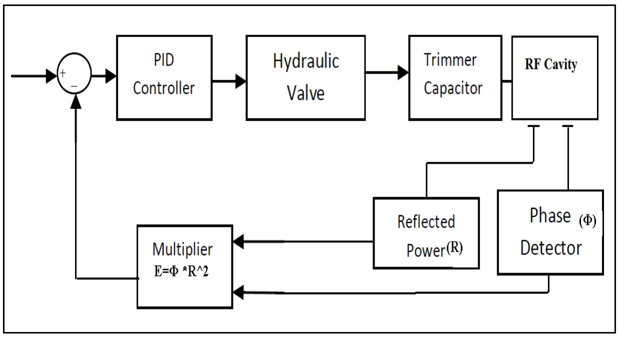

Fig.7. Block Diagram of hydraulically driven Trimmer control system

Both Dee voltage stability and relative phase stability between three dees are very important parameters for beam acceleration. The Dee voltage regulator will maintain the dee voltages and therefore a portion of additional power will reflect back to the generator and increase plate dissipation. This situation lasts until the error is significantly large and valve starts responding to the input.

The system [3] consists of a Siemens 315-2DP PLC based PID controller, Hydraulic Valve Actuator, Trimmer capacitor, RF cavity, Phase detector and Reflected power meter. A 16 bit (15bit + 1 sign bit) analog input channel is used to sense the position of the trimmer. Linear potentiometer is used to measure the position of the trimmer. Due to the very high Q of the cavity, Dee voltage amplitude and phase is very sensitive to the movement of trimmer. Both phase error and reflected power are measure of frequency detuning and ideally both are zero when the cavity is properly tuned. Primarily the control system operates on the phase error between Dee-in and Dee pick-up signals. But due to measurement noise, non-linearity, delay in loop, the system lead to oscillations. Lowering of proportional gain of PID control loop will reduce the oscillations but settling time will be increased as well. So a variable gain system is proposed which comprises of phase error (Φ) and reflected power(R). The reason behind the variable-gain control design is –Firstly, when the error is small a low-gain design should be in effect to ensure low sensitivity to high-frequency measurement noise and, secondly, when the error becomes large due to low-frequency thermal events, a high-gain design should be active to ensure a high level of low-frequency tracking performance. Reflected power does not provide the direction of detuning (i.e. whether positive or negative), it gives only the magnitude of detuning. Feedback signal is the product of phase error (Φ) and the square of reflected power (R) to have non-linear gain. This control logic improves the system performance by averaging the two signals when minima of phase and reflected power differ.

The step response is plotted in Fig.4. Popov stability criterion is examined and both the signals are scaled accordingly. It is observed that the system takes good care of noise and both rise time and settling time is improved. Similar response is also observed in practice.

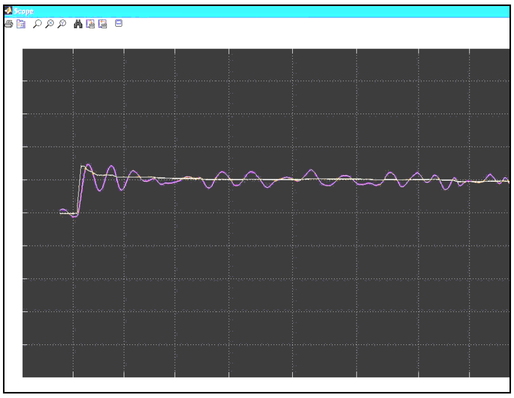

Fig.8. Step response of the system

LOW-LEVEL RF

RF signals from 3-phase generator unit, pass through Manual phase shifter unit to get adjusted of the relative phase between three signals, if any phase asymmetry occurs. Then the signal passes through two closed loop Systems – Dee voltage regulator unit (DVR) for amplitude regulation and Phase regulator unit for phase regulation. As Phase loop produces some residual amplitude modulation, amplitude loop precedes the phase loop. After phase regulator unit the signal is directly amplified to 1kW level by solid-state driver amplifier and then to 80 kw level by Eimac tetrode based tuned final rf power amplifier for feeding to the main Dee cavity.

DVR (as shown in Fig.9) is based on AD834JN RF Modulator that modulates the RF drive signal according to the error signal between highly stable dc reference (REF01) and the feedback sample obtained from Dee pick-up signal.

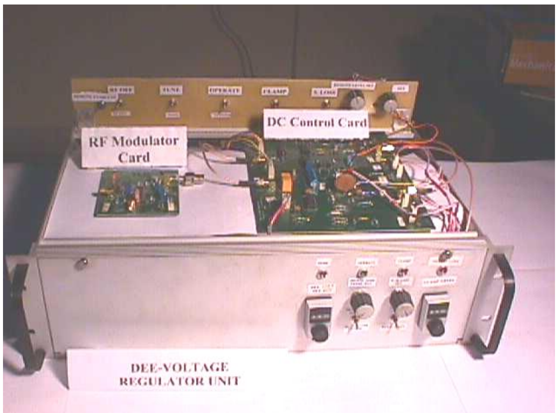

Fig.9. Dee Voltage Regulator Unit

In 3ϕ-generator, phase shifting of 120^o is done by double mixing and auxiliary transmission line based technique, thereby making insensitive to frequency change. Phase imbalance between 3 channels is $<\pm 1^o$ and amplitude unbalance is $<\pm 0.2$ dB with harmonic content less than –40dBc. The manual phase shifter (as shown in Fig.10) is based on classical I&Q modulator using M/ACOM QH-6-4 quad hybrid, MCL-ZAS-3 electronic attenuator and MCL-ZFSC-2-1 splitter. In normal operation $\pm 15^o$ variation is sufficient and output signal balance is $<<\pm 0.05$ dB with harmonic content < –38dBc.

Any deviation from sample phase from the reference phase is detected by the phase detector and produces dc error signal, which, in turn, controls online I&Q phase modulator and lock the phase to its reference within working limit of $\pm 60^o$ and error bandwidth of 1 kHz. Phase detectors, based on double balanced mixer, have been fabricated using MCL-RPD-1 having response of 8mV/degree in +8dBm saturated mode.

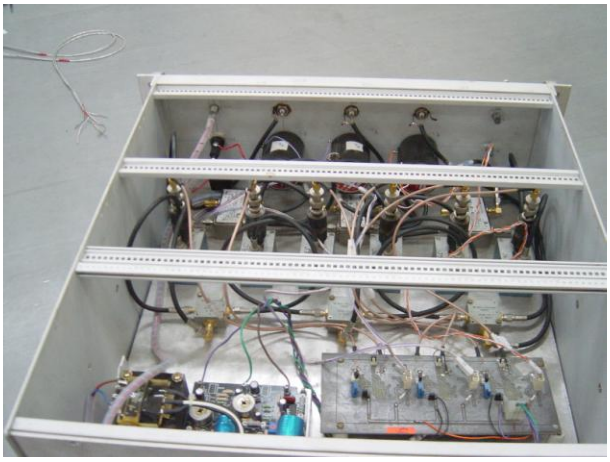

Fig.10. Manual Phase Shifter Unit

CONCLUSIONS

A major modification in the logic of trimmer control loop has been incorporated in the system. It ensures minimum RF power requirement and also minimum reflected power towards the RF power source. The amplitude loop and phase loop stabilities have been improved substantially

ACKNOWLEDGEMENT

The author would like to thank all staff of VECC and especially to RF (Electrical &Mechanical) staff for their active participation and help to carry out the job.

REFERENCES

[1] S. Som, et. al., “Development of RF system for k500 superconducting cyclotron”, Proceedings of International Cyclotron conf. at Catania, Italy 2007.

[2] S. Som, et., al., “RF cavity analysis using PC Superfish code”, IEEE Russia conference, MIA-ME-1997, p.179.

[3] Aditya Mandal, et. al., “Advanced closed loop trimmer control system for the fine tuning the RF cavity of k500 superconducting cyclotron”, presented in this conf. InPac-2011 at IUAC, New Delhi.

The above work has been funded by DAE, Govt. of India.