DEVELOPMENT OF RF SYSTEM FOR K500 SUPERCONDUCTING CYCLOTRON AT VECC, KOLKATA

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Abstract
The 3-phase rf system of Superconducting (Sc) cyclotron has been developed in the frequency range 9 – 27 MHz with amplitude and phase stability of 100 ppm and $\pm 0.5^{o}$ respectively. Each dee along with half-wave coaxial cavity develops peak voltage of 100kV having fed with rf power (~80kW) from each of the three high power final rf amplifiers. Like main Dee-cavity, each amplifier is tuned by moveable sliding short. Each of the four identical Bridge-T network in the grid are driven with maximum power of 150 watts. The amplifier, based on Eimac 4CW#150000E tetrode and operated in class-AB mode with power gain 22 dB, requires dc power supplies (P/S) like, Filament P/S 15.5V/215A, Grid P/S -500V /0.5A, Anode P/S 20kV/22.5A and Screen P/S 1.5kV/1A, at its four terminals. A PC-based stepper motor controlled sliding-short movement system is used for tuning the cavities at different frequencies. The closed-loop amplitude and phase regulators are based on RF modulator and I&Q modulation technique respectively. Dee voltage pick-off signals are used as feedback. A PLC-based interlock system protects the rf system as well as operating personnel. Measurements of rf parameters at various resonant frequencies of the amplifier cavity have been done. The frequency response of the input circuit of the amplifier has been measured using VNA.

RF SYSTEM

The block diagram of the rf system of sc cyclotron is shown in Fig.1. In this master-oscillator-power-amplifier (MOPA) system, the rf signal from a highly stable (better than 0.1ppm) frequency source is fed to a wideband three-phase (3ϕ) generator, which provides three rf signals of same frequency (with 120^{o} phase difference between each other) and then through various amplifier stages coupled to three resonant cavities by coupling capacitors.

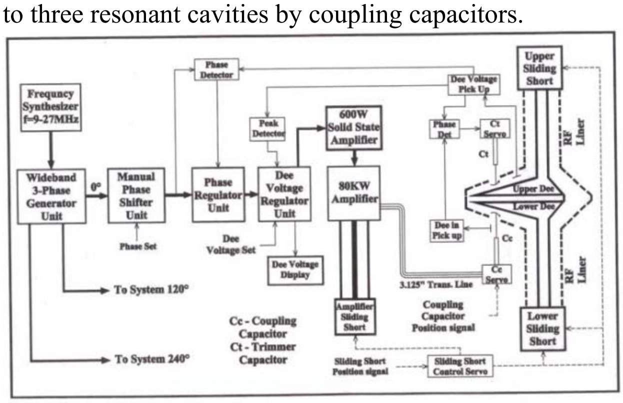

Figure 1: Block diagram of K500 RF system at VECC

Dee Stem: Each of the three separately excited half-wave (λ/2) resonant cavities (as shown in Fig.2) consists of two one-end short-circuited foreshortened quarter-wave (λ/4) coaxial transmission line (Dee-stem) terminated by the accelerating electrode (Dee) near the median plane. Dee-stem consists of uniform coaxial line (in air) and also tapered line (in vacuum). The tapered line makes it possible to reduce the total power dissipation in the cavity, limit the current in the sliding short and minimize

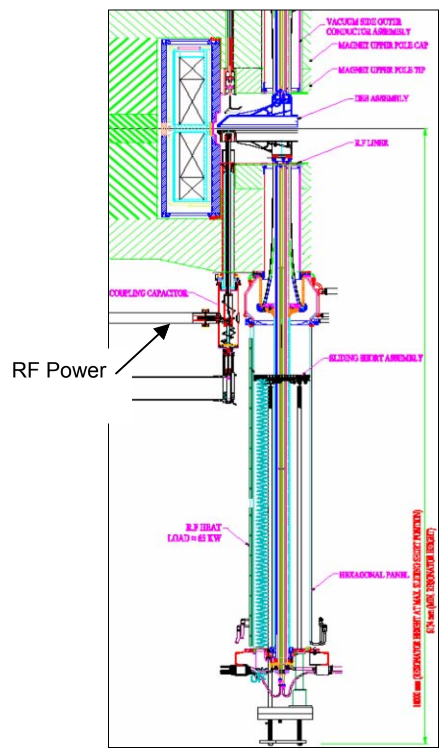

Figure 2: coaxial rf cavity including dee and dee-stem

the mode interference problems. The RF performance [1] of the cavity has been analyzed by using SUPERFISH code [2]. The coaxial line (in air) is made 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).
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.4) with sliver-graphite (99%Ag +1%C) contact ball at the tip. The inner and outer conductors are aligned concentric preferably within ±0.25 mm., because large asymmetry may give rise to uneven stress on the contact finger. The contact resistance is of the order of 0.7mΩ per finger. 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.

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

Insulator: A high voltage pure (99.5%) alumina insulator (loss factor ≤4 x 10^{-4}, Dielectric constant ≥9.6, tensile strength ≥ 3.5 N/mm^2) forms boundary for the vacuum envelop and allow the sliding short to operate in air. The dimension of the insulator is 285.75 mm. OD x 266.7 mm. ID x 228.6 mm. L and its end surfaces are metallized with molybdynum-manganeese brazing alloy to nominal 25µm thickness with 5µm nickel final coat.

Coupler: The drive power from final power amplifier is fed to the cavity by a hydraulically driven vacuum variable coupling capacitor ($_{Cc}$) through 3-1/8 inch rigid coaxial transmission line with 50Ω characteristic impedance. 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 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 C_c is 90^o.

POWER AMPLIFIER

Three high power final rf amplifiers have been developed and installed at the vault. Each rf amplifier (Cross-sectional view as shown in Fig. 3) is based on Eimac 4CW 150,000E water-cooled tetrode and has max. 100 kW output at 50Ω impedance. The output tank circuit of the amplifier consists of a λ/4 type variable length coaxial cavity. Like main Dee cavity, the short-circuited coaxial cavity is also tuned by the precise movement (with a resolution of 50 µm) of the sliding short (see Fig. 4 & 5) within the operating frequency range of 9 to 27 MHz under unloaded condition. The shape of the amplifier cavity is similar to that of the main cyclotron cavity, except only the length, which is 2184 mm. for amplifier.

An inductive coupling loop is inserted along one side of the cavity (through the sliding short) at 1/5th voltage point to reflect nearly constant impedance at the anode of the tetrode. But as the length of the loop is comparable to operating wavelength, this assumption is not valid. So, by loop area trade-off it is kept in the required range. Anode shell heavily loads the tank circuit, thus reducing the cavity length and shifting the cavity higher order modes beyond 66 MHz. The output rf power (up to $100kW_{max}$) is taken out at 50Ω impedance through this inductive loop, which is matching the high cavity impedance to 50Ω.

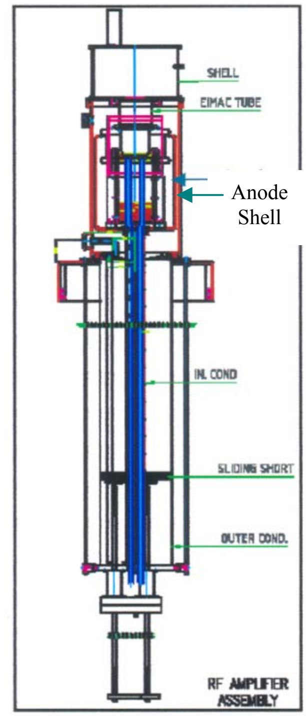

Figure 3: Cross-sectional view of high power rf amplifier

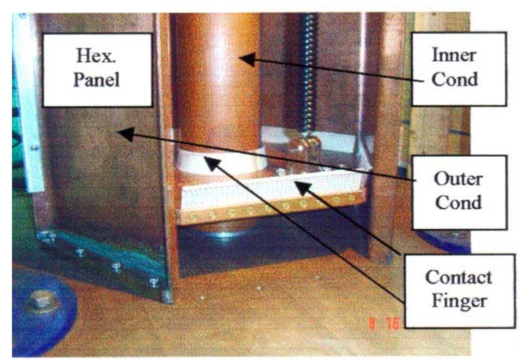

Figure 4: Sliding short contact fingers for amplifier

The four identical Bridge-T networks (see Fig. 6) in the grid of the final amplifier (shell) are driven with equal power levels of up to 150 watts each. VSWR of the input circuit of the amplifier has been measured using VNA (See Fig. 7) and obtained max of 1.14 at 18.18 MHz.

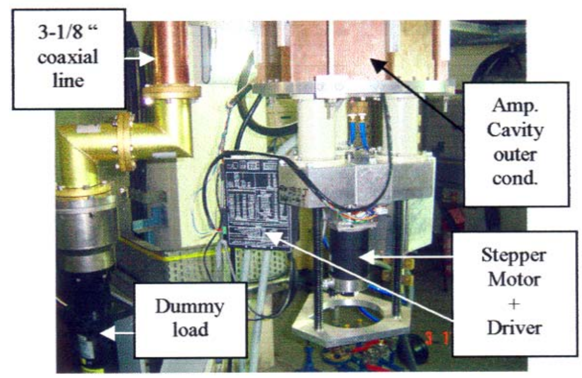

Figure 5: Stepper motor assembly with amplifier sliding short

Figure 6: Input circuit (assembled) for amplifier

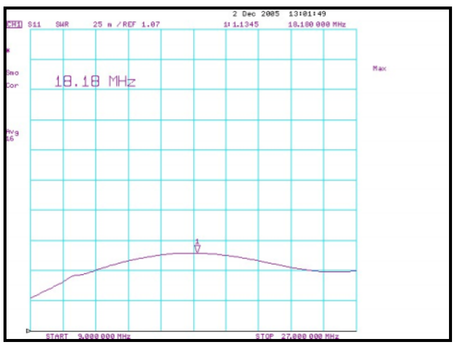

Figure 7: VNA measurement of input VSWR

The anode of the tetrode is coupled to the cavity by a cylindrical Blocking capacitor as shown in Fig. 7.

The measured unloaded Q of the cavity varies from 4300 to 1800 and the measured loaded shunt impedance values vary from 5kΩ to 1kΩ within 9 MHz to 27 MHz.

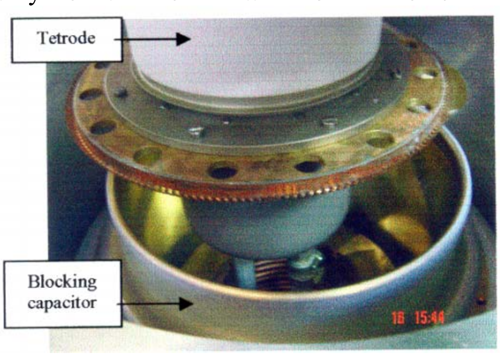

Figure 8: Tetrode assembly with blocking capacitor

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 600W level by *solid-state driver amplifiers* (2 nos. of ENI#A300) and then to 100kW level by Eimac tetrode based tuned *final rf power amplifier* for feeding to the main Dee cavity of the cyclotron.

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* is based on classical I&Q modulator [3] 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.

DVR is based on AD834JN RF Modulator [4] 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.

Any deviation from sample phase from the reference phase is detected by the *phase detector* that 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. The phase detectors are used as window comparator to generate trigger signal if the phase of rf signal, due to fast phase change, crosses the predetermined value, and thereby indicating the occurrence of Sparking.

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CONCLUSION

Three nos. of high power final rf amplifiers including PC-based stepper motor controlled drive system for sliding shorts have been developed and installed at vault. LLRF control electronics have been developed and tested successfully. Assembly of main dee cavities are in progress and warm rf test of these cavities is expected to be carried out soon.

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