THE RF-SYSTEM OF THE CERN "NEW LINAC"

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Summary

The rf-system of the CERN "new linac"[1] consists of ten separate amplifier chains of modular construction, with individual fast amplitude and phase regulation systems, together with a slow tuning servo. All the servomechanisms act on the low-level part of each chain, without any high-power modulators.

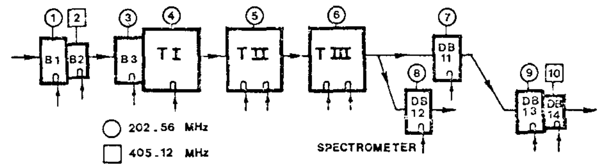
Constructional details of the rf hardware are given and performance figures presented.

Structure of the Rf-system

The basic design decision was to assign a separate amplifier chain to each of the ten resonators and to start at an rf-level of 2 Watts. The feedback circuitry can thus be built around high-speed, low power components, such as varactors or PIN-diodes driven by operational amplifiers.

The "semiconductor part" comprising servomechanisms and rf amplifiers up to 400 W, is essentially the same in each chain, and only the "tube part" is specifically tailored to the power requirements. Table I gives a summary of the latter.

A common master oscillator generates a quartz-controlled reference signal of 202.56 MHz, which is amplified in a pulsed 300-W-amplifier and distributed via the phase-stable reference line running along the resonators in the accelerator tunnel. Directional couplers derive the input signals for each of the 8 fundamental frequency chains with near-to-ideal decoupling. The second-harmonic chains 2 and 10, receive their input signal from doublers in the corresponding 202-MHz chains 1 and 9; this arrangement simplifies the phase setting of the double resonators.



Chain	Designation	Amplifier configuration (Tube type, output power)				
1	BUNCHER 1	RS 2024 30 kW				
2	BUNCHER 2 Second harm. (405 MHz)	RCA 7651 3 kW	RCA 4665 22 kW			
3	BUNCHER 3 Energy Corrector	RS 2024 30 kW				
4	TANK I	RS 2024 30 kW	TH 170 0.5MW	TH 170 2.5MW		
5	TANK II	RCA 7651 5 kW	RS 2024 90 kW	TH 170 0.9MW	TH 170 2.5MW	TH 170 2.5MW
6	TANK III	RCA 7651 5 kW	RS 2024 90 kW	TH 170 0.9MW	TH 170 2.5MW	TH 170 2.5MW
7	DEBUNCHER 11	RCA 7651 5 kW	RS 2024 90 kW			
8	DEBUNCHER 12	RCA 7651 5 kW	RS 2024 90 kW			
9	DEBUNCHER 13 Bunch Rotator	RCA 7651 5 kW	RS 2024 90 kW			
10	DEBUNCHER 14 Second harm. (405 MHz)	RCA 7651 3 kW	RCA 4665 22 kW			

Table I General layout of the rf system

The Anatomy of a Chain

The feedback loop

The block diagram is shown on Fig. 2. The rf modulators work below 100 mW but are well shielded. Stray rf from the high power components interfered however, with the video circuits causing oscillations. With some additional filtering in these circuits, the problem disappeared.

Cross-coupling between the amplitude and the phase loop is small, except in the cavity when this is detuned for beam load compensation. In practice, the cross-coupling remains tolerable and the feedback loop is well behaved.

Bandwidth is limited by the phase shifts due to delays in the loop (total length about 50 m for the linac tank loops) and additional phase shifts in the components. It was found that an adequate safety margin was achieved at a bandwidth of about 150 kHz.

Other limitations to the bandwidth are resonances, one of which is shown in Fig. 3. If this resonance crosses the unity gain line, the loop oscillates at the frequency of the resonance. One cause of the resonances is higher modes in the linac cavities but, in this case, the next higher mode was more than 1 MHz away and caused no difficulties.

More troublesome are the standing waves between the final amplifier and the cavity, which can be considered a short circuit, some 50 kHz from the nominal frequency. This short circuit, transformed by the feeder line, combines with the amplifier load impedance and builds up parasitic resonances. The line length can be set between two extremes, $\lambda/4$ apart :

(a) "Maximum-Q" : resonances are at maximal distance from the nominal frequency ; highest safety

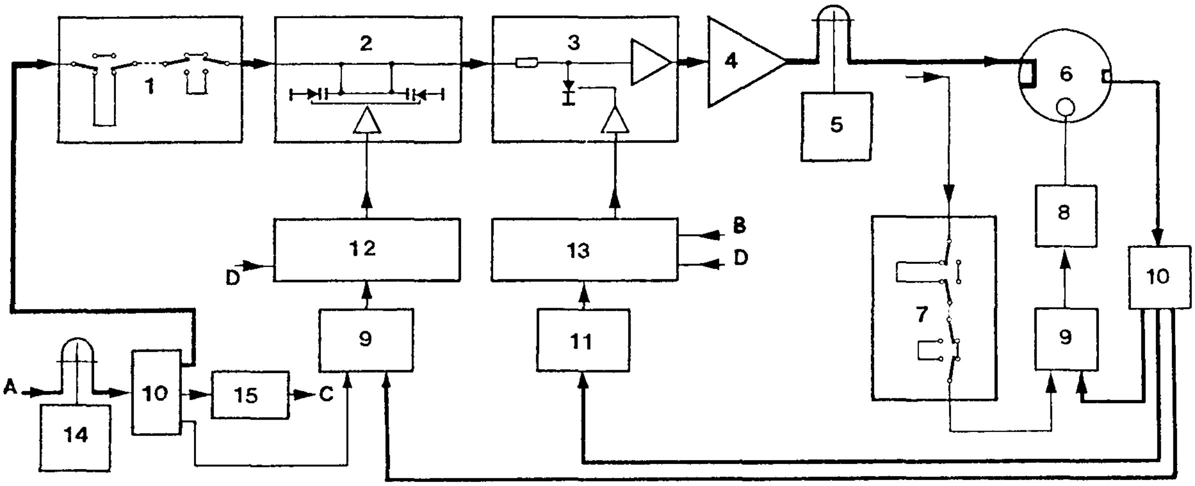


Fig. 2 Block diagram of the Feedback System
(1) 6-bit variable delay line for adjusting loop phase; (2) fast phase modulator with varicaps; (3) fast amplitude modulator with PIN diodes; (4) rf power amplifiers; (5) trombone; (6) cavity; (7) variable delay line for setting the cavity tuning; (8) control of the slow tuning loop; (9) phase detector; (10) 3-way divider; (11) amplitude detector; (12) phase feedback control; (13) amplitude feedback control; (14) trombone for setting cavity phase; (15) frequency doubler;
Signals (A) rf reference; (B) amplitude reference; (C) rf reference for 2nd harmonic cavity (chain 1 or 9); (D) feedforward signals to improve the transient response when the beam comes in.

margin against overvoltages ; however, the tank rise-time is slowest and self-compensation of beam loading is poor.
(b) "Minimum-Q" : resonances are minimal distance, with the other effects at the opposite extreme.

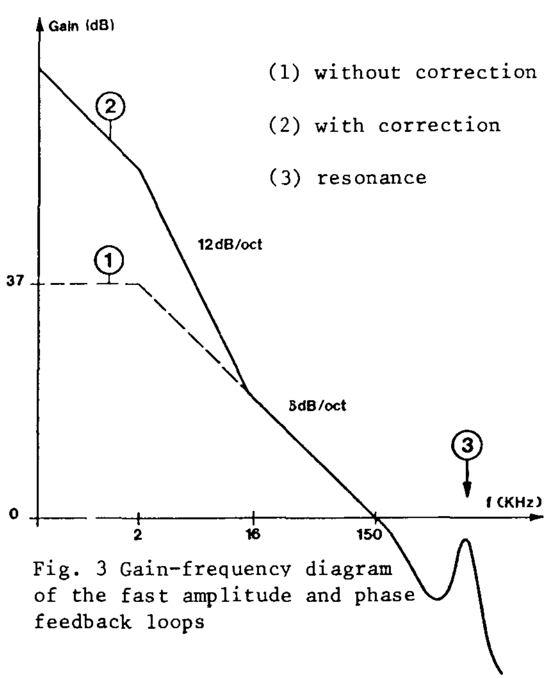


Fig. 3 Gain-frequency diagram of the fast amplitude and phase feedback loops

In practice, one starts with the safe "maxi-Q" setting and works towards the "mini-Q" until the best compromise is achieved.

In the case of DB 13, which needs high power at the end of a very long cable, the safest solution was to include a circulator in the feeder line.

Amplifier

The 400-MHz power amplifiers are commercial units using the RCA tetrodes 7651 and 4665. These are the only amplifiers that were bought ready-made. The other amplifiers have been developed here at CERN.

The transistor amplifiers are 4-stage linear amplifiers with a wide dynamic range. The final stages consist of 4-module units each delivering 100 W. Thanks to the low duty cycle, the transistors operate without cooling fins.

Three other amplifiers were developed. One started as a grounded cathode stage of 40-kW output for 300 W of drive. The Siemens RS 2024 CL was selected as the best tube for the job. By tuning-out the cathode inductance and using screen-grid inductor neutralization, the design goal was achieved. A production model suffered from a parasitic oscillation at 2.3 GHz, which took some time to cure. Although one amplifier of this type was used operationally for about a year, on the grounds of increased simplicity and higher output power, this configuration was aborted to a grounded-grid, grounded-screen design. With this change, only 36 kW with a drive of 400 W was obtained.

To ensure an ample reserve of power as drive for the high power stages, an additional amplifier known as the "pre-driver" was designed and built. Using more drive power, the RS 2024 was driven up to an output power of 100 kW. A particular feature of the RS 2024 stage is the re-entrant plate cavity with an integral "POLYFLON" plate blocker. This is a Teflon cylinder with electroformed copper on both sides, making a distributed capacitance with high dielectric strength. The 14-kV plate supply is obtained from a capacitor bank.

The "pre-driver" also used an RCA 7651 in a grounded-grid, grounded-screen circuit. An output power of 8 kW for a drive power of 400 W has been achieved. The plate supply is 5 kV, derived from a capacitor bank.

Both amplifiers use identical screen-grid supplies; these are 1 kV, 1 A units with built-in protection against overcurrent. Fast acting protection is provided for both amplifiers by means of ignitron crowbars triggered by plate overcurrent pulses.

Eight identical 2.5-MW amplifiers are used in the final and drive stages of all tank chains. They are equipped with the TH 170 triode, a water-cooled version of the well-proven vapor-cooled TH 470 triode. It was found that this type is the most economical solution for this low duty cycle machine. The amplifier can, however, also accept the TH 116 triode, the water-cooled equivalent of the TH 516, to deliver > 50% more power.

The amplifier is a re-development of the original CERN linac amplifiers ; modifications include larger resonator diameters (up to the very limit of the first circumferential mode), improved RFI shielding, different tube cooling, completely redesigned input circuit, easily adjustable output coupling loop, and grid neutralization. The latter cured instabilities at the leading edge of the pulse that were initially attributed to tank-multipactoring due to very similar symptoms. As in the earlier version, the amplifier is two floors in height. The upper part extends into the equipment gallery with a removable cover that is part of the output resonator ; from here a tube may be changed in about 20 minutes. The lower part is based in a service tunnel and comprises the infra-structure such as blowers, filament transformer, drive mechanisms, etc., as well as rf-input and output ports imbedded in their respective resonators. A thyristor-controlled filament supply and associated electronics with an analog multiplier keeps the filament power constant despite mains fluctuations and resistance drop of the thoriated tungsten cathode. In addition, it provides smooth turn-on and turn-off during a 3-minute ramp.

HV-modulator and charging supply

Each of the tank-chains is equipped with a 40-kV plate supply, consisting of an LC pulse-forming network (PFN), an ignitron as high-power switch, a pulse transformer to provide voltage step-up and ground separation, and a crowbar system with ignitron and resistive termination.

All the (two in Tank I or three in Tank II, Tank III) amplifiers of a chain are connected in parallel to their respective pulse transformer. The modulator is designed for a pulse length of up to 1.1 msec (H^-operation), but is at present only equipped with condensors for 250 µsec (proton-operation) ; therefore, many special features of the circuit such as the resetting of the pulse-transformer core by the capacitor charging current, or the mere size of the transformer or the capacitor cabinet, may seem much overdesigned at first sight.

The three PFNs are charged by a common 25-kV supply via decoupling diodes. When the preset voltage is reached on the capacitors, the charging is interrupted by firing a set of parallel thyristors across the 200-V mains side of the HV transformer 50 Hz chokes limit the current in this mode as well as during the charging cycle, thus providing very high efficiency together with a minumum of mains disturbance. The modulator was designed by A. Faltens of LBL.

Due to the internal resistance of the PFN arrangement, the output voltage depends on the load current which would normally change with the rf drive. A stabilization circuit is therefore included, which consists of cathode resistances in the tubes together with a Zener-diode bank for polarization at 1200 V. This reduces the variation of the plate currents to less than 10% between full output power and quiescent state. Severe overdrive of the output tubes however, results in excessive plate currents, low plate voltage and reduced rf output. To avoid a latch-up condition with the amplitude-servo loop closed, the maximum drive power has to be limited by an adjustable threshold in the feedback circuit.

Rf plumbing

All cavities are fed by means of low-loss feeders. Air dielectric semi-rigid Flexwell cable is used in the buncher and debuncher chains, with 1"7/8 or 3"1/8 diameter. The three tanks are fed by stub-supported rigid lines of 230/100 mm diameter, supplied by Spinner, via dust-proof trombones having a range of 360° at 202 MHz. The feeder lines can be relatively easily opened for test purposes and short circuits or dummy loads inserted. While there are trombones in the feeds to all tanks and in the inputs to the final amplifiers for Tanks II and III (these for phase equalization), it was found possible to operate with fixed lengths of feeder for the other resonators, having first determined the optimum electrical length.

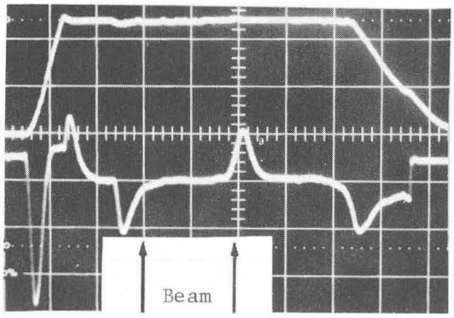
Couplers supplied by Spinner are placed at strategic points in the feeders. Detector heads are connected directly at the couplers and their video output is taken back to the monitoring system. The heads are of special design in order to achieve reliable power level indication. Each has two diodes, a balanced output, and a low-pass 225 or 450 MHz microstrip-filter incorporated. Low-pass filters are also inserted in signal paths from the tanks to attenuate higher harmonics passed by the tanks.

Control interface

Normal operation of the rf system is through the general control system of the linac. In addition, there is a full set of local controls, centralized for each chain, giving access to test points and all mechanical and electrical settings. Each power amplifier chain and the HV modulators are protected by independent, hardwired interlocks.

Performance

This is best described by the following photos taken for Tank III, while operating with a beam current of 100 mA, i.e., 2/3 of the maximum value.

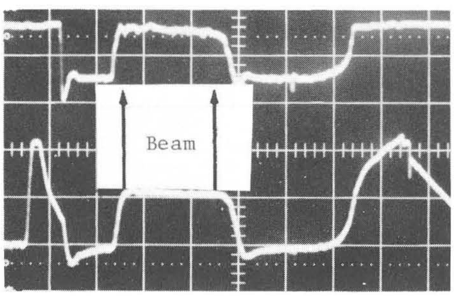


tank amplitude

tank phase
1.6°/div.

time base
50 μsec/div.

The amplitude shows a transient of 1.3%. This has negligible effect for the tanks downstream. To improve the transient response of the feedback loops, feedforward signals can be supplied when the beam comes in. This facility is not used at present as the system works satisfactorily without it.

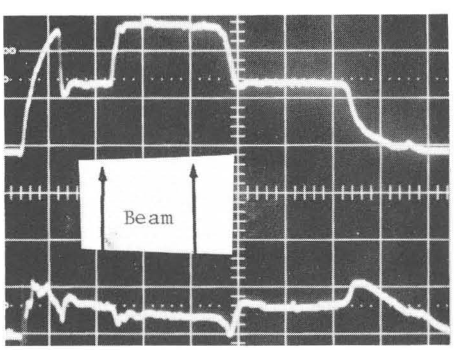


amplitude
control
7dB/div.

phase control
20°/div.

time base
as before

The second photo shows the control signals operating on the loops. During operation, it is essential that enough power is available during the beam time. Also, due to the fact that the phase modulator has only a limited range of 80°, one has to make sure that the loop delay is properly adjusted (by item 1 in Fig. 2). Note the large amount of correction required due to the heavy beam loading of 100 mA. This can also be seen on the next photo.

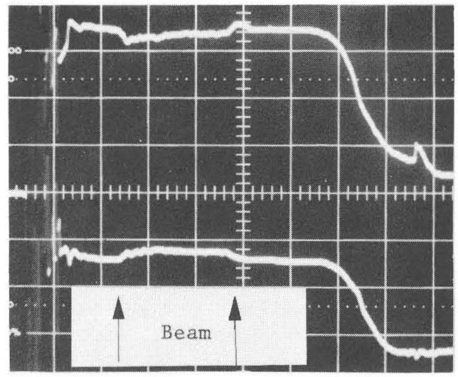


Time base
as before

forward power

reverse power

This shows signals from the directional coupler at the output of the upstream final amplifier, after rectification by the detector head. 2.7 divisions correspond to 2 MW.



time base
as before

plate volte
10 kV/div.

plate current
50 A/div.

The plate voltage and current for the final upstream amplifier are shown above. Due to the constant-current configuration of the 2.5-MW stages, the load current and hence the plate voltage show only moderate variations.

Conclusion

The system described gives adequate performance over the full range of beam current, up to 150 mA, without any resetting of parameters ; if this were applied (e.g. for feedforward, adjustment of tank loops and tank tuning for minimum reflection, etc.), there would be potential for improvement at the expense of a more complicated operation.

The system was not designed with low cost as primary goal. However, we feel that the low expenditure of 3.5 MSfr. (including all temporary labor) deserves mentioning.

Reference

1 E. Boltezar et al., "The New CERN 50-MeV Linac", proceedings of this conference.