DESIGN, CONSTRUCTION AND OPERATION OF THE NEW CERN SC RF SYSTEM

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Abstract

A fast cycling RF-system giving high energy-gain per revolution was required to overcome the intensity limitations set by space-charge in the CERN SC. All other frequency modulation methods being discarded for power reasons, a high Q system tuned by a rotary capacitor was chosen.

The rotary capacitor, constituing the most critical part, requires excellent vacuum, forced cooling on all RF electrodes and high mechanical precision. The mechanical problems which, in the early stage of the design, were feared most, proved to be solvable. However, considerable effort was necessary to obtain sufficient reliability of vacuum and cooling circuits. Specially shaped stator blades are used to furnish an optimized frequency modulation programme.

The RF circuit design by means of models and computer programmes was initiated at first at CERN and continued later by industry. Detail hardware design and construction was performed by industry, further development and running-in by CERN.

The system is performing satisfactorily and has permitted acceleration of the design proton intensity per machine pulse.

1. History

Excellent results of the new sector-focussed cyclotrons were reported in 1963 at the "Conference on Sector-focussed Cyclotrons and Meson Factories" concerning intensity, beam quality and extraction efficiency[1]. The utilization of mid-plane hooded arc ion sources with high acceleration voltages was essential to achieve this result. The CERN SC magnet did not allow the conversion of the old SC into a sector-focussed fixed frequency machine while keeping the maximum energy unchanged. Therefore a first proposal for a conversion of the SC RF system into a fast cycling system with an acceleration time of 950 µs, permitting the use of a hooded arc ion source in the SC was made in 1963[2][3]. Detailed investigations lead to a "Proposal for the Improvement of the 600 MeV Synchrocyclotron"[4]. Because all other frequency modulation methods had to be discarded for power reasons, a high Q system, tuned by a rotary capacitor, was chosen.

2. RF System Design

2.1 Design parameters

Peak accelerating voltage V_{aa} = 30 kV

Acceleration time t_{aa} = 1350 µs

Pulse repetition rate f_{rep} = 466 Hz

Max. frequency f_{max} = 30.3 MHz with $\frac{df}{dt} = 14 \frac{\text{MHz}}{\text{msec}}$

Min. frequency f_{min} = 16.77 MHz with $\frac{df}{dt} = 0$.

2.2 RF circuit design

The design of frequency modulated RF systems has to take account of many limiting circumstances, which become particularly hampering when the maximum proton energy of the cyclotron exceeds several hundred MeV, because mechanical dimensions and necessary frequency swing increase at the same time. A careful system design was necessary to obtain the required frequency range, the frequency-time dependence, the variation range of the lower frequency end and last but not least to keep the RF power consumption and the electrical field strength between the capacitor electrodes within admissible limits[5]. (Fig. 1). Computations were checked at first on a 1:5 scale model, later on a 1:1 model.

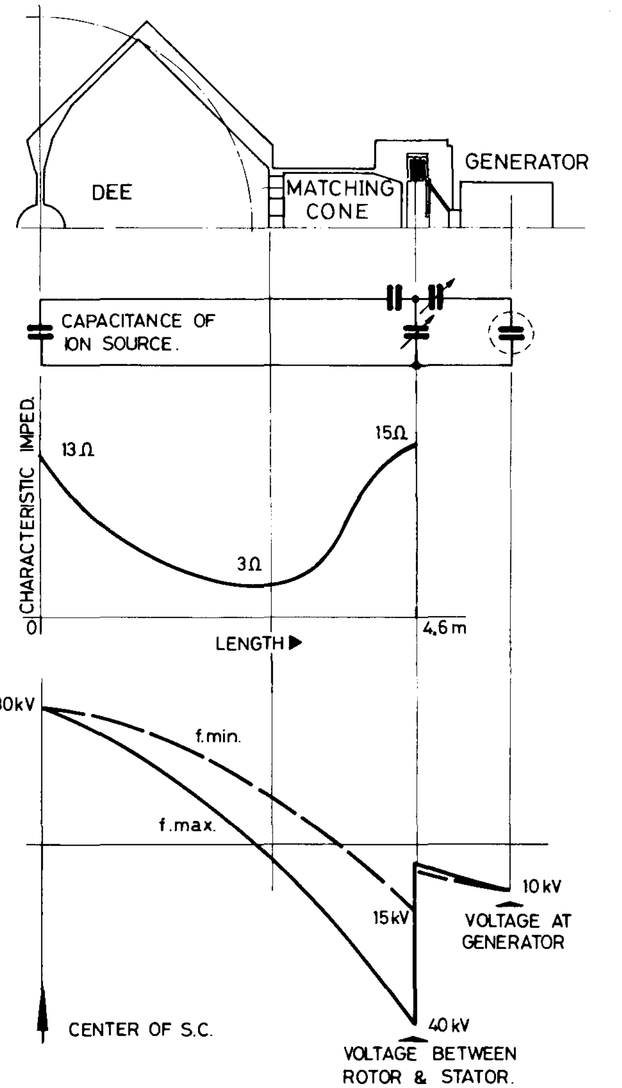

Fig. 1 Mechanical Layout, simplified Electrical Diagramme, Characteristical Impedance and Voltage Distribution along the Resonator

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2.2.1 Accelerating electrode In order to keep the power requirements as low as possible, a cutback dee with radially varying impedance has been adopted. In view of the experience with the old SC[6][7] a crossmode suppressing slot bridged by damping resistors was adopted. The RF voltage distribution on the dee is described in[8].

2.2.2 Rotary capacitor The basic electrical design was much influenced by the existence of the magnetic fringing field behaviour as well as by the requirement to prevent circular resonances on the rotor. The drive motor was therefore placed inside the rotary capacitor to permit a fully symmetrical coupling between the RF generator and the rotor. The exact motor location is in the region where the fringing field changes sign. The electrical connection between the accelerating structure and the rotor is an inhomogeneous transmission line formed by two conical concentric conductors ("conus"). Four variable vacuum capacitors placed in parallel to this part of the line near the three coaxial feedthroughs into the SC vacuum tank allow the adjustment of the lower end frequency. The electrical coupling between the rotor and the "conus" is effected by a 20 nF disk capacitor with 0.3 mm gap.

2.2.3 RF generator The RF generator is self-excited and has to delivery about 180 kW peak. The admissible output capacity is limited to 300 pF in order not to decrease the limited frequency swing of the system. At the same time the grid phasing should be such to assure a high generator efficiency as well as stable operation over the entire range. Therefore a power-tetrode was chosen, YL 1390, with 150 kW admissible plate dissipation[9]. The coaxial power tube was integrated into a coaxial feedback circuit using a ferrite core as feedback transformer (Fig. 2). This circuit provides excellent feedback conditions all over the working frequency range (deviation from optimal feedback phase angle $< 12^\circ$). The coupling of the RF generator to the rotor is made by means of a variable coupling capacitor which ensures that the load of the generator is constant over the entire frequency range. The amplitude of the acceleration voltage as function of frequency can be varied by a function generator[10] which drives a series anode voltage modulator triode RS 1041 W.

2.3 Mechanical design

2.3.1 Accelerating electrode The dee consists of a frame of aluminium profile girders, covered by roll-bonded copper clad aluminium plates with integrated cooling channels (Evidal plates), together with the dee liner it is carred by the pump-manifold of the vacuum chamber and may be removed relatively easily on a rail system.

2.3.2 Rotary capacitor (Fig. 3) In order to the required capacity variation between 500 pF and 7000 pF a rotor diameter of 1440 mm with 3 rows of 16 blades each was required. Water cooling channels were drilled into the teeth. They prevent bending of the plates due to unequal current load. The same solution has been adopted for the stator blades and the disk capacitor electrodes.

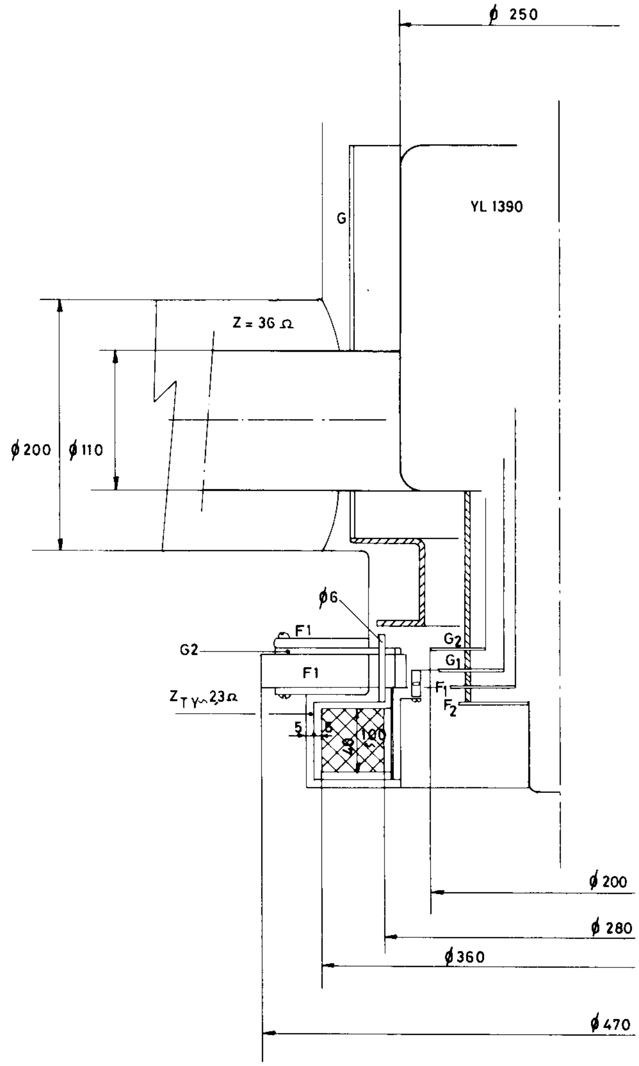

Fig. 2 View of Coaxial Feedback Circuit of Self-excited 150 kW RF Generator

The gap between the 3 rows of the rotor and the 4 rows of 16 stator blades varies between 1.3 and 4.0 mm. These figures are based on extensive experimental investigations about admissible field strength between electrodes at radiofrequencies[11].

The rotor, designed for a maximum speed of 2200 rpm is sitting on two preloaded ball bearings on a countilevered shaft. The mechanical losses in the ball bearings of about 1 kW are cooled off by an oil circulation system which at the same time cools the rotating face-seal. This seal prevents in connection with a rotating turbopump baffle and a intermediate vacuum system the back-streaming of oil from the bearing hcamber into the main vacuum chamber.

Details about the stator blade shape as well as the application of a bridge circuit to prevent the destruction of the ball bearings for the rotor are given in [12].

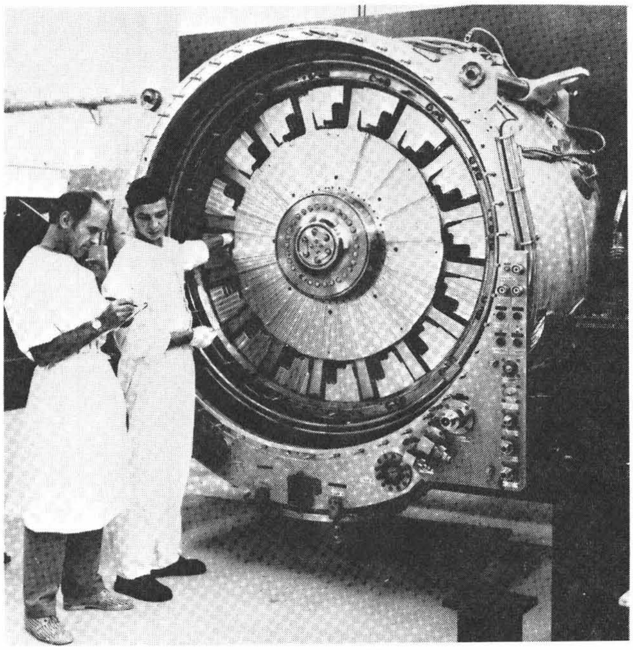

Fig. 3 Rotary Capacitor Assembly

The volume of the rotco vacuum chamber made out out Al-Mg alloy is about 6 m^3, the total internal surface 90 m^2. It is pumped separately from the SC vacuum tank by a turbomolecular pump with 4000 l/sec pumping speed. In order to prevent vacuum contamination by decoposition products of elastomer joints most of the vacuum joints have been made as soft-aluminium-wire joints. Water cooling tube connections use also metal-metal joints.

3. Development of the Project

3.1 Initial studies

Following the choice of a mechanically modulated system computer and 1:5 scale model studies for the RF circuit were carried out at CERN between 1965-1968. At the same time studies of the HT behaviour of electrodes and ball bearing life-time tests under RF currents were performed.

3.2 Detail design and construction by industry

Because of a decision of CERN not to increase staff, calls for tenders to industry were sent out in 1967 and 1968 and a contract was signed in February 1969 with the AEG-Telefunken, Accelerator Department, for the design,construction and installation of a "New SC RF System" under the overall responsibility of the firm. The delivery was due by the middle of 1971. The progress of the project was, however, slow inspite of the effort of the firm and considerable help from CERN.

3.3 Transfer of equipment and responsibility to CERN

Finally in 1973 an agreement was signed under which CERN received the equipment in the second half of 1973, largely untested, not fulfulling the specifications and without any guarantee. Under CERN responsibility and with some help from the supplier the equipment was made operational.

4. Experimental Results and Improvements

4.1 Mechanics

The mechanical stability of the two rotcos over a period of about 3000 hours of running has been very good. The vibration level, measured on the Rotco housing, does not exceed a few µm in the working frequency range. No trouble was caused by the suspension of the rotor bearings on alumina ceramics. The wear of the bearings is negligible under present running conditions. Considerable effort, however, had to go into the complex of the oil-cooling system for the bearings and the rotating surface seal. It seems that the latest development of an integrated oil cooling system inside the rotco offers the required safety margin under all running conditions. Modifications of the connections for the internal cooling circuits now permit the dismantling of the rotary capacitors within a few hours.

4.2 Vacuum

The size of the rotco housing, the number of internal supply lines as well as the use of nonconventional joints in the original execution have caused considerable difficulties.

Sources of difficulties have been : metal-ceramic connections, excessive use of bellows, use of brazing techniques, residues of flux causing corrosion. After considerable modifications of the vacuum system and replacement or redesign of many parts, the working pressure in the two Rotcos is now between $2 - 5 \times 10^{-6}$ torr, and occasionally as low as 8×10^{-7} torr.

4.3 Electrical supplies and electronics

All electrical and electronic supply units for the new RF system are duplicated and in case of breakdown the reserve installation may be switched into operation without major interruption. The thyristor frequency converters used for the rotor drive motor have been particularly troublesome.

4.4 RF generators

Although the two self-excited RF generators work well and with good efficiency over the entire frequency range on a dummy load, difficulties arise in practical operation when - due to a discharge in the RF system - the load changes. The present feedback system then allows osciallations at higher frequencies. The filters designed to suppress these oscillations are constantly improved. It is not simple to assure a satisfactory power and voltage safety margin.

4.5 RF operation of the system

First tests and running-in of the installation had to be done without the cyclotron vacuum chamber (Fig. 4). Essential items for running the the system were :

(a) a pulsing system, permitting to excite the system only at a reduced rate (1:1 - 1:16),

(b) a discharge stopper system, which cuts the RF programme and the bias supplies immediately in case of an excessive bias current,

(c) a potential equalizing coil in the oil vapour contaminated forepump duct, preventing RF-breakdowns.

After the very time-consuming elimination of a major quantity of mainly low level faults conditioning was possible until reaching 20 kV at the dee mouth with full frequency range with a duty-cycle of 100%.

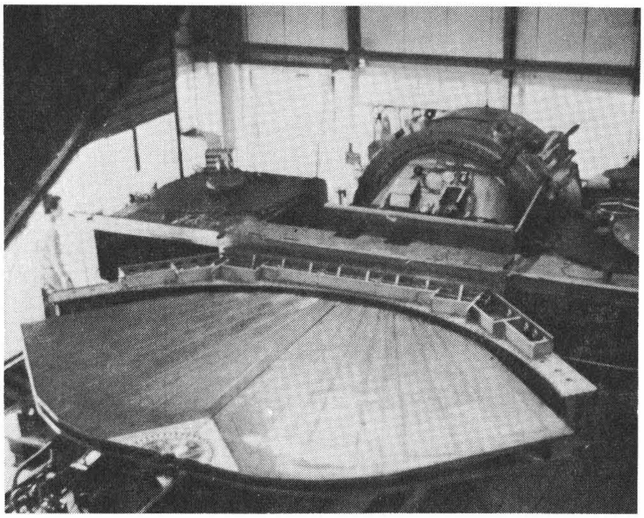

Fig. 4 The Dee, Dee-liner, Pump-manifold and Rotary Capacitor of the new RF-system during Installation at the Test Site

The measurement of the frequency time programme was one of the next major steps. It was carried out by means of two computing counters with a time base of 500 MHz and gave the required accuracy of 10^{-4}. Comparisons with the nominal curve and orbit computations showed that there was no urgent need for a subsequent stator blade machining in order to reach the specified frequency programme. The variation of the lower frequency end as function of the rotor position now does not exceed 8 kHz.

After installation of the new accelerating electrodes in the cyclotron vacuum tank, first tests with magnetic field were undertaken. The magnetic shielding for the rotary capacitor proved to be fully satisfactory in respect to eddy-current losses in the spinning rotor and to the drive motor efficiency. However, RF operation with magnetic field proved to be much more difficult. Bias voltages had to be optimized differently and at higher duty cycles relatively frequent discharges occurred in the rotcos.

SC operation was started with 20 kV HF and 1:16 duty cycle (Fig. 5). Continuous conditioning permits operation now with 1:4 duty cycle. It is expected that the application of pulsed bias voltages, as proposed by NEVIS, as well as the suppression of the forevacuum duct across the HF carrying parts of the rotco coax-lines will further improve the system behaviour. Furthermore cooling of some tuning elements has to be improved.

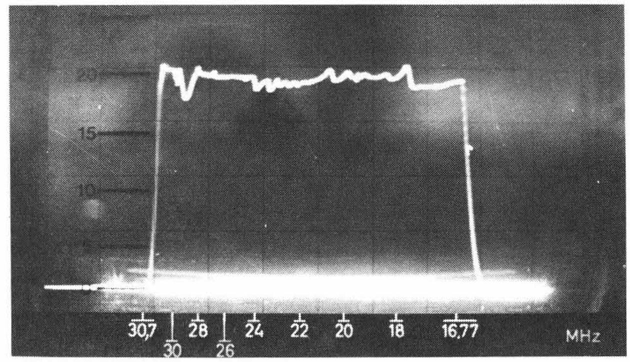

Fig. 5 20 kV RF Voltage on the Dee Mouth as function of Frequency

The variation of the lower end frequency exceeds the required range between 17.3 MHz (for internal target operation) and 16.77 MHz (for extracted proton beam).

After a few weeks of operation leaks developed in the dee electrode cooling system due to residual brazing flux corrosion. Aluminium tube welding techniques were developed and the entire dee had to be repanelled with new Evidal plates during spring 1975.

5. Future Plans

Apart from measures to improve the performance of the present system, a project is at present being worked out, to modify the system such that ^{3}He, α and Deuterons can be accelerated[13]. For this the frequency has to be shifted downwards by means of additional coaxial lines between the present rotco and the accelerating electrodes.

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DISCUSSION

F.G. TINTA: Since you consider modifying your RF-system so that ^{3}He, α-particle and deuterons could also be accelerated, can you say how much such a modification would cost?

H. BEGER: We are at present working out the project for approval. Our first rough estimate is that it will cost more than one million Swiss francs. The system has to be designed for quick change-over from one particle to another in order to protect the operators from too much radiation during these changes.

F.G. TINTA: What percentage of the operating time can be expected to be used for accelerating ^{3}He and ^{4}He?

H. BEGER: At present we are giving about 40% of the available machine time to the ISOLDE people. Probably they will receive in future a quarter of this time for ^{3}He, which would mean that during about 10% of the total available machine time we would accelerate ^{3}He.