THE RF-SYSTEM OF THE AGOR-CYCLOTRON

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The main components of the AGOR RF-system are described and their performance discussed. A good agreement has been found between the measured and calculated properties of the resonators. The servo systems for amplitude and phase (analog) and tuning (digital) meet their specifications, but some modifications to simplify operation will be implemented. In the first two years of operation the system has shown to be reliable: it has operated for extended periods at 90 % of the maximum required Dee voltage and close to the maximum frequency with very little problems.

1 Introduction

The superconducting cyclotron AGOR accelerates ions of all elements over an energy range from 5 MeV per nucleon for heavy ions like Pb to 200 MeV for protons. The orbital frequency of the ions ranges from 6 to 31 MHz. The ions are accelerated by three independent resonators with an acceleration voltage up to 85 kV in 2^{nd}; 3^{rd} or 4^{th} harmonic mode, thus requiring a frequency range of 24 - 62 MHz for the RF system.

2 Resonators

The conceptual design of the RF resonators has been described previously [1]; only its main features are summarized here. The resonators are coaxial $\lambda/2$-cavities, which are symmetric with respect to the median plane and are located in the valleys of the magnet poles. The Dees have a spiral shape similar to that of the hill sectors. Because of the high frequency (up to 62 MHz) the use of a vacuum-feedthrough/insulator is not possible: its capacitance and the space it occupies would considerably lower the highest attainable frequency. Consequently the whole resonator is under vacuum.

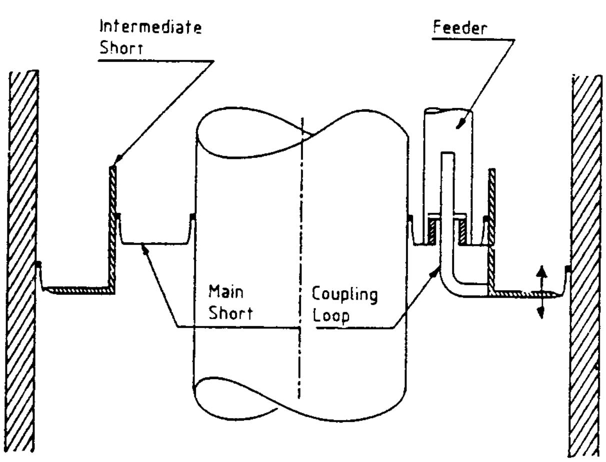

fig. 1 Schematic drawing of the sliding short and coupling loop

The RF-power is fed into the resonator via a variable coupling loop mounted in the sliding short of the upper half resonator. The size of the coupling loop is adjusted by varying the vertical distance between the concentric main and intermediate sliding shorts (fig. 1).
The RF signal for the regulation of phase and amplitude of the acceleration voltage and for the tuning servo system is provided by a small inductive pick-up mounted in the sliding short of the lower half resonator.

2.1 Mechanical aspects

The fact that no vacuum-feedthrough/insulator close to the median plane can be used complicates the mechanical design of the resonators.
In particular, the positioning of the Dees within a tolerance of 0.5 mm in the cyclotron center requires a complicated mechanism. The half Dee on each side of the median plane is connected to the inner conductor of the coaxial line through its support structure. The whole is then fixed in a positioning system outside the vacuum at the end of the coaxial line (2.5 m from the median plane). This system has six degrees of freedom. In order to verify the position of the Dees a precision-machined jig has been made. Despite careful adjustment it has been observed that the position of the Dee varies by a few tenths of a mm as a function of the position of the shorting plate.
The positioning mechanism of the shorting plates is equipped with four differentially pumped sliding seals per half resonator. The rectified chrome-plated tubes, that connect the shorting plate to its external positioning mechanism, move through these seals. Furthermore the tubes serve as feedthroughs for the cooling water, for the relative movement between main and intermediate shorting plate and for RF power and pick-ups. The choice for sliding seals instead of long bellows was imposed by building constraints and mechanical complications.

The upper and lower half of the resonator are not mechanically connected across the median plane. As some RF current can be expected to flow from one half to the other RF contacts have been mounted in the central region and at the outer radius of the Dees, where the upper and lower halves touch.

The Dees have been shaped by hammering 3 mm copper sheet on a mould. To guarantee their mechanical stability they are mounted on a stainless steel and aluminium inner structure. Care has been taken to minimize the heat transfer from the Dee to the structure. The clamping of the Dees on the structure allows for differential thermal dilatation.

In the central region, where each Dee has a different and complicated shape and where the tolerances are too tight to be met by hammering techniques, the Dees are equipped with solid copper "noses". The pillars across the median plane have been made of molybdenum because of its superior sputtering and mechanical characteristics as compared to copper.

2.2 Vacuum aspects

The AGOR-cyclotron is not equipped with an intermediate vacuum between the RF-liner and the magnet pole. The copper liner thus acts - together with inner and outer conductors of the coaxial lines and part of the cryostat - as the vacuum chamber. The force on the vacuum chamber (30 tonnes per pole) is transferred to the magnet poles through 39 bolts located in the hill sectors, where the vacuum chamber has a thickness of 18 mm, a clamping system on the outer diameter and the outer conductors of the coaxial lines. In the valley sectors, where the thickness of the hammered copper is 3 mm, a stainless steel support structure has been mounted on the outside of the vacuum chamber in order to limit the stress in the material. Due to rolling and welding, the μ_r of the steel has locally increased to 1.05 but the azimuthal and median plane symmetry are not significantly disturbed.

2.3 RF characteristics

The RF properties of the resonators have been calculated with a transmission line model in which a half resonator is divided into 28 sections with a rectangular or circular cross section. The parameters of the model have been adjusted to reproduce the voltage distribution along the acceleration gaps and the shorting plate positions measured on a simple full scale model with a frequency range of 46 - 62 MHz. With the transmission line model the position of the sliding short, the height of the coupling loop, the Q-factor and the required power have been calculated. To define the geometry of the cooling leads, a more detailed spatial distribution of the power dissipation was made by estimating the inhomogeniety of the current distribution in each section from the real 3D-geometry. The power dissipation obtained from this approach is 10 - 15 % higher than the one from the transmission line model. In fig. 2 the calculated shorting plate position, height of the coupling loop and Q-factor corrected for the above mentioned increase of the power are compared with measurements on one of the resonators. Apart from the Q-factor the agreement between calculation and data is good, showing the validity of the simple model. The power needed for a given acceleration voltage has been found to be in good agreement with the calculations, in contrast with the bad agreement for the Q-factor.

The resonators are capacitively coupled due to the penetration of their electric field across the hill sectors in the median plane. The coupling has been determined by tuning the resonators to nearly the same frequency and measuring the frequency response of each resonator while exciting another one. From these measurements a coupling capacitance between the resonators is 0.00005 - 0.0002 pF has been deduced, in qualitative agreement with an estimate based on calculations of the field penetration.

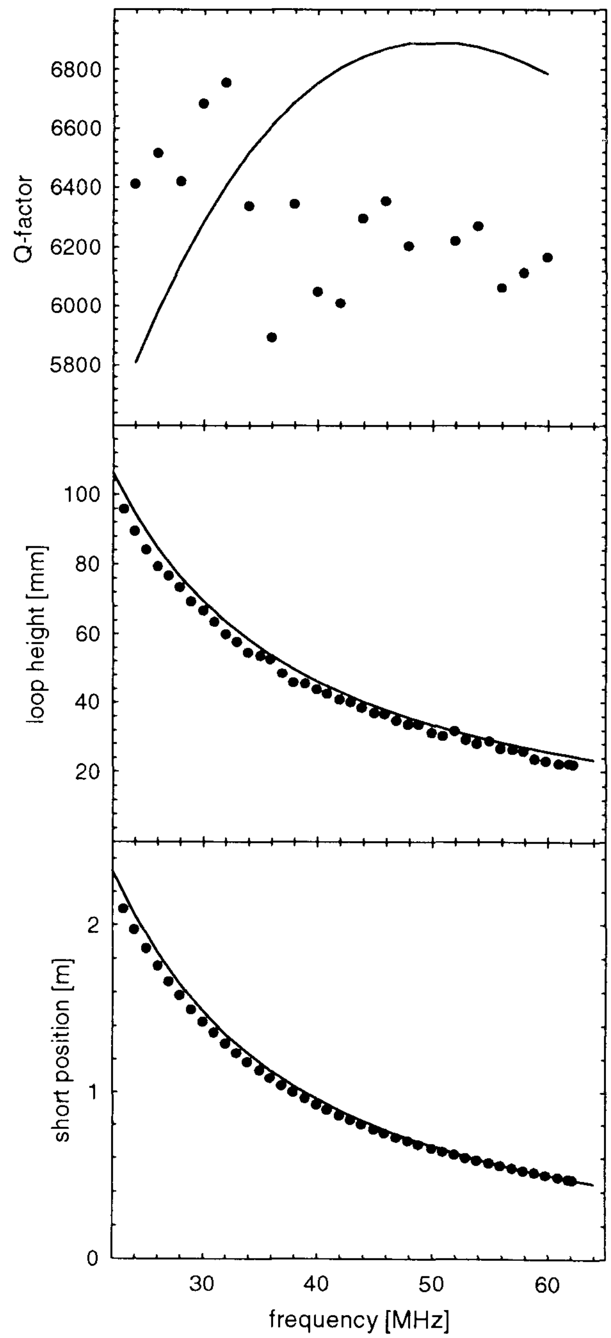

fig. 2 Resonator characteristics as a function of frequency

2.4 Thermal characteristics

The resonator cooling is provided by fourteen cooling circuits with a total waterflow of 14 m^3/hour per resonator. The layout of the cooling circuits has been designed such that the temperature increase at any point is below 10K. The inlet temperature of the cooling water is kept constant within 0.2K The corresponding change in resonance frequency is an order of magnitude smaller than the bandwidth of the resonator. The experience gained shows no need for a more sophisticated system, *e.g.* stabilizing the average of entrance and exit temperature.

The thermal drift of the resonance frequency is about 10^{-3} at the maximum power of 25 kW, which corresponds to a displacement of the main shorts of 2 to 0.5 mm over the frequency range. The thermal time-constant of the resonator is 25 s, which requires a speed of the tuning servo loop, which acts on one of the intermediate shorts, of 0.3 mm/s.

3 Control system

The RF system is controlled by the operator with a PC-based interface written in Borland Pascal. The subsystems are controlled by 8051 μ-processors with a variety of interface modules (analog I/O, logic I/O, motors). The software in the 8051 consists of a general module server and dedicated tasks. It has been written in C.

3.1 Tuning and matching

The initial position of the main and intermediate shorts are obtained by interpolation from a table. Because of the compression of the magnet by the magnetic field (0.5 mm at 3 T) the position of the main short requires fine adjustment for each new beam. Up to now this is done using a network analyzer. An automatic system for searching the maximum signal on the inductive pick-up at very low power (20 mW) below multi-pactor is under development. The position for the intermediate short, *i.e.* the size of the coupling loop needed for proper matching ($\rho \leq -35$ dBc), requires no fine adjustment.

During operation the drift in the resonance frequency is regulated by a digital servo system with a cut-off frequency of 1 Hz. The input to this system is the phase difference between the incident wave and the current in the short. The system starts operating when the Dee-voltage exceeds a few kV. If the phase difference exceeds 2° RF the intermediate short in the lower half resonator (trimmer) will make a step proportional to the phase difference (typically 10 μm). In order to maintain the midplane symmetry the trimmer is kept in a range of ± 2 mm around its reference position. When the maximum is reached both main shorts are moved in small steps until the trimmer has arrived to with in 0.3 mm of its reference position. The stepsize is such that the servo system is able to compensate their effect between successive steps. Although the phase sensitivity of the short movement varies a factor 6 over the frequency range, a satisfactory behaviour of the system over the full frequency range has been obtained with one set of parameters.

3.2 Amplitude and phase stabilization

The stability of the amplitude and phase of the acceleration voltage is 10^{-4} and 0.1° RF respectively. These values stem from the aim to allow single turn extraction. To maximise the bandwidth of the stabilization loops compensation circuits for the poles of the resonator and the amplitude and phase modulators have been included. Bandwidths of 10 kHz and 50 kHz at an operating frequency of 60 MHz have been obtained for the phase and amplitude stabilization respectively.

The phase measurement is done directly at the RF frequency using ultra-fast comparators and ECL-logic. The phase is obtained by integrating the output of the ECL-logic.

4 Operating experience

4.1 Multi-pactor

During the initial commissioning in Orsay switching on the resonators was found to be very difficult, which was erroneously interpreted as being due to strong multi-pactor. The real cause turned out to be the very fast protection circuit in the power amplifier, which detected a high VSWR during the transient when applying RF power to the resonator. After modification of the circuit no further difficulties in switching on the resonators were observed. With magnetic field multi-pactor in the high impedance part of the resonator, which prevents proper operation, exists only below 1 kV and is easily passed. Close to the sliding short (in vacuum) continuous multi-pactor has been inferred from the decoloration of the copper. Since this is on the low impedance end of the resonator it does not influence operation.

On its path out of the cyclotron the beam passes very close to the Dee of resonator 3. In order to avoid RF deflection of the beam the RF liner connecting the upper and lower halves of the resonator has been placed between the Dee and the beam path. The initial design of this closure (fig. 3) was optimized to have small capacitance towards the acceleration electrode and to minimize the vertical component of the RF electric field.. During commissioning it turned out that the resonator suffered from very frequent discharges, in contrast to the other two. Inspection revealed that the discharges took place at the closure.

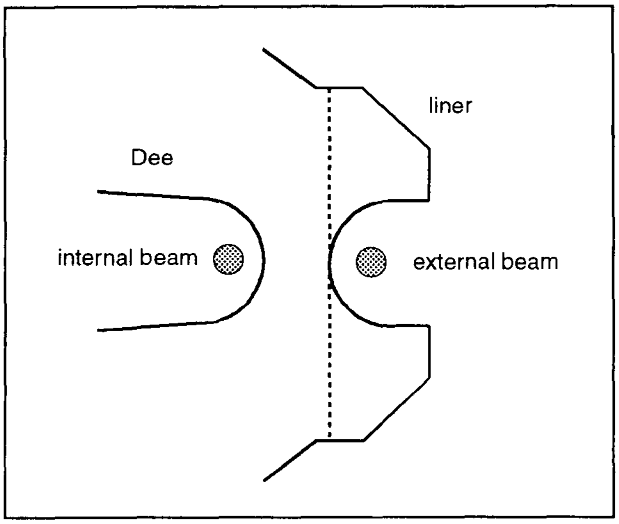

fig. 3 Geometry of Dee and liner of resonator 3; dashed line indicates modification to remove multi-pactor

Calculations indicated that the conditions for multi-pactor were fulfilled in the stub-like closure. It was then concluded that the discharges were caused by the plasma produced by the multi-pactor. The design of the closure was modified (dashed line in fig. 3) to remove the multi-pactor conditions, after which no further problems occurred.
The 190 MeV proton beam, which is extensively used (almost half of the beamtime in 1997), has been the most demanding one for the RF system, requiring an acceleration voltage of 75 kV (RF power 21 kW) at a frequency of 60 MHz. Conditioning to reduce the frequency of discharges to about once an hour takes three to four hours when the system has been operated at low voltage and frequency for a long period. The frequency of discharges then gradually decreases with time to once every four to eight hours. At voltages below 60 kV discharges are very rare: the RF system may operate for several days without a single discharge.

4.2 Sliding contacts

As mentioned, the main sliding short is moved under full power, *i.e.* at a current density of 35 A/cm in the contact fingers, during re-establishing the mid-plane symmetry of the resonator. Although a considerable fraction of the discharges at the highest voltage is associated with this operation, which takes place a few minutes after applying power to the resonator, inspection of the contacts after two years of operation did not reveal any damage or decoloration indicating excessive heating of the contacts.

4.3 Amplitude stabilization

The amplitude modulator is directly controlled by the comparator of setpoint and actual value of the acceleration voltage. The diode characteristic of the modulator thus causes a considerable variation in gain over the voltage range, requiring the use of a variable attenuator to avoid oscillation of the high-gain amplitude loop. In open loop (in reality: gain = 1) the closed-loop settings of the modulator and attenuator are such that too little power is available to pass multi-pactor, thus requiring a different setting. As a result the passage from open-loop to closed-loop is rather delicate. To remedy this problem, which has so far prevented automatic recovery from discharges, a new amplitude modulator has been built. The response has been linearized by adding a logarithmic amplifier, compensating the exponential diode characteristic, and the control circuitry has been modified such that the comparator of set and actual values operates around null.

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References

[1] S. Brandenburg et al., Proc. 12th Conf. on Cyclotrons and their applications, Berlin, May 1989; pg. 197