THE RADIO-FREQUENCY SYSTEM OF THE NAC 200 MeV SEPARATED-SECTOR CYCLOTRON

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Summary. The radio-frequency system has been operational since October 1985. An important feature is the very wide frequency range (6 to 26 MHz) required for the acceleration of both light and heavy ions. Two resonators are used (positioned in opposite valleys of the four sector-magnets). The peak voltage is 250 kV per accelerating gap. This requires 100 kW per resonator at 26 MHz. Frequency variation is achieved by symmetrical adjustment of two short-circuiting plates in each resonator or by adjustment of two large capacitor plates. Capacitive coupling is used between the resonator and the 50-ohm power cable (15 m long). The two 150 kW power amplifiers are situated outside the cyclotron vault. Phase and amplitude control and stabilization is performed by equipment developed and constructed at the NAC.

After initial difficulties due to multipacting a "kick-pulse" starting method was developed. Automatic restoration of resonator voltage after a discharge has recently been implemented. Successful operation up to 250 kV at several frequencies between 12,5 and 26 MHz has been achieved. The rf system has successfully accelerated beams to 66 and 200 MeV.

Components of the radio-frequency system

During the design stage of the separated-sector cyclotron the following requirements were established for the rf system. Two resonators are required, with the resonator frequency four times the orbital frequency. The frequency range is 6 to 26 MHz. 1 MeV energy gain per turn is required to enable single-turn extraction of 200 MeV protons. The accelerating electrode forms two accelerating gaps per resonator and it is approximately triangular in shape, with 3,5 m sides. It is referred to as the inner delta and the maximum required rf voltage is 250 kV (peak).

A half-wave coaxial transmission-line resonator was selected to enable the maximum frequency to be reached with such a large inner delta. A 3 m long transmission line at the top and a similar line at the bottom provides a frequency range between 12,5 and 26 MHz by means of an adjustable short-circuiting plate in each line. It was not feasible to use longer lines therefore the lower part of the frequency range has to be covered by symmetrical adjustment of two large capacitors (each plate has 3 m^2 area), which are mounted above and below the inner delta. The central and top parts of a completed resonator are shown in Fig. 1 and 2. The main characteristics are listed in table 1 ("Position" is the distance from the inner delta).

Resonators

Resonator chamber. The vacuum chamber encloses the inner-delta high-voltage electrode and was manufactured from 40 mm thick stainless-steel plate. The dimensions are similar to those of the valley vacuum chambers (4 m triangular chamber, 1 m high). The outer delta lining fits closely inside the stainless-steel vacuum chamber. It is made from 3 mm thick copper plate and forms the rf conducting surface connecting the grounded electrodes of the accelerating gaps with the outer conductors of the transmission lines. Contact fingers are used between the vertical and horizontal sections. The copper plates are water-cooled using copper pipes (12 mm square with 10 mm diameter hole) attached by silver-eutectic welding, on the side opposite to the rf surface. Horizontal slits (on the sides of the two adjacent magnets) allow entrance and exit of the beam particles. In the injection region the magnet prevents the

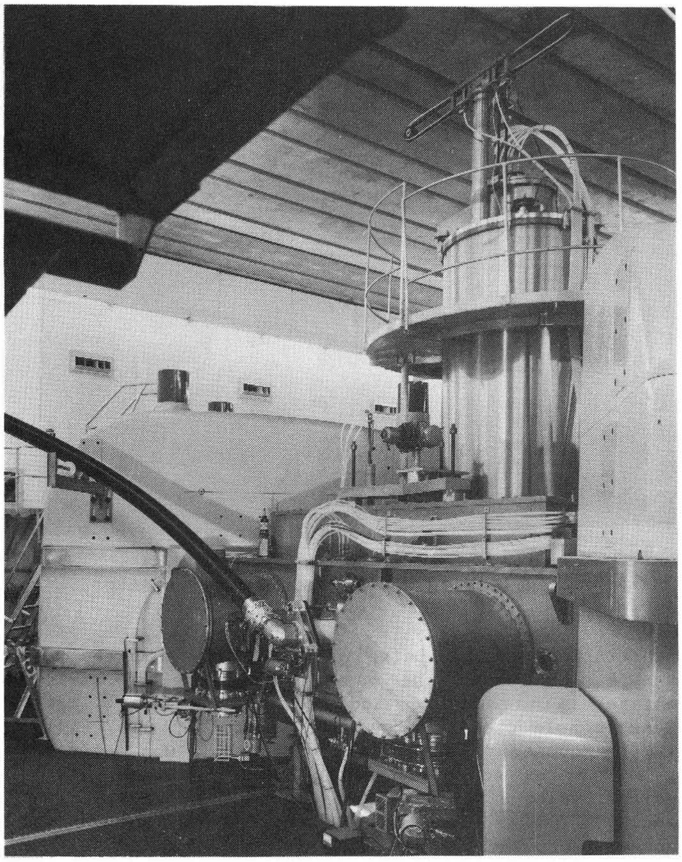

Fig. 1 A completed resonator between two magnets

Table 1

Measured resonator characteristics

Frequency MHz	Q-value	Short-circuit position mm	Capacitor position mm	Power at 250 kV
26,0	16300	550	380	100
18,2	17150	1380	380	81
12,5	16200	2850	380	71
8,7	11500	2850	55	
5,6	6300	2850	15	
4,7	4300	2850	10	

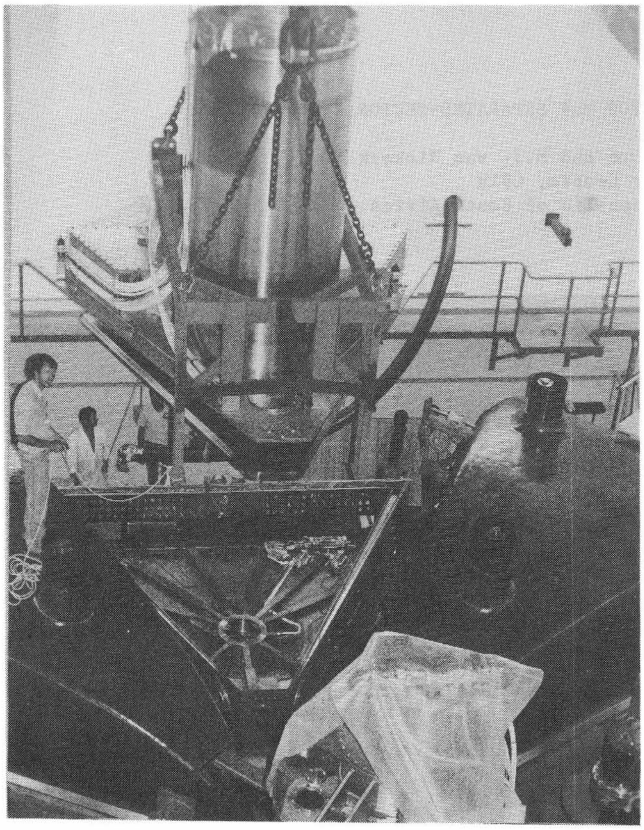

Fig. 2 Lifting the top part of a resonator

accelerating gap from being in a position where the beam packets will cross the gap at the time of maximum voltage. In each top and bottom plate is a 1,4 m diameter hole where the outer conductor of the coaxial line is mounted. The position of the hole was optimised by studies on scale models to find the point giving optimum voltage distribution along the accelerating gaps. A trapezoidal box is provided at the top and another at the bottom, in which the adjustable capacitors are mounted. The back wall supports the coupling capacitor, two fine-tuning capacitors and two vacuum-pump chambers.

Outer conductors. Each outer conductor is 3 m long and has an internal diameter of 1280 mm. It was manufactured by copper electro-forming. The wall thickness is 32 mm and the spiral water-cooling channel was provided during manufacture as an integral part of the wall thickness. After electro-forming, the cylinders were machined to 0,2 mm tolerance and each inside surface was honed. Electrical contact between the outer cylinder and the liner of chamber is made by a metal C-ring.

Inner conductors and their support. The inner conductors were also produced by electro-forming. Each is 3,5 m long and 500 mm in diameter with 25 mm wall thickness. Three parallel spiral channels, integral with the wall, provide for water cooling. The highest heat density occur on the inner cylinder (2 watt/cm^2) and the total dissipation can reach 30 kW. Each inner cylinder is carried by a support-structure mounted on the outer cylinder. Adjustment of the structure allow exact alignment between inner and outer cylinders. Vacuum sealing is performed by an end plate, bolted to the outer, and 600 mm diameter bellows, connected between the end plate and the inner cylinder.

Inner deltas. Each inner delta consists of an upper and a lower half, with each half bolted to an inner cylinder. The skin, made from 3 mm copper plate, is supported by a radial-arm framework made from stainless steel as shown in Fig. 2. The flat copper skin is joined to the copper inner cylinder by a conical transition piece using silver-eutectic welding. All copper surfaces are water-cooled. Each accelerating gap electrode has a machined profile and two drilled cooling channels along its 3,6 m length. They are welded to the opposite edges of the flat inner delta plates. Electrical contact between the upper and lower halves is made by two rows of contact fingers, one at the front and the second at the back. All cooling pipes of the inner delta and the inner cylinder are routed through the inner cylinder.

Short-circuiting plates. A short-circuiting plate has to provide electrical contact between the inner and outer cylinder at different positions along the cylinders. The electrical part is formed by a 5 mm thick copper plate with an outer diameter of 1265 mm and a central hole 511 mm in diameter. Contact fingers are welded along the entire length of the outer and inner perimeters. The fingers are made from 0,25 mm thick dispersion-strengthened copper plate. This material has electrical and thermal conductivities close to that of pure copper and has adequate mechanical properties (proved by tests). It allows the maximum current density of 35 A/cm (RMS) on the inner part to be carried by 20 mm long fingers, with a temperature rise of 70°C. Each finger is 18 mm wide and has two 6 mm diameter silver contacts mounted on it. The edge of the copper plate is machined with a sharp ridge to facilitate welding of the thin fingers to it. Owing to the 0,2 mm accuracy of the cylinders, the movement of the inner fingers is restricted to 3 mm and the outer fingers to 6 mm. The outer fingers are 35 mm long and 18 mm wide. To minimize mechanical stress in the fingers they are pushed to make contact and pulled back to release contact. The operating system of the contact fingers is mounted on the aluminium supporting ring for the copper plate. A second aluminium ring is moved away from the first ring by applying air pressure to six bellows spaced evenly around the ring. This relative movement is conveyed to 12 dual-arm linkages which change the direction of movement, thus allowing the finger-pushing sectors to move toward the cylinders as shown in Fig. 3. Each finger is pushed centrally between the two contacts while a spring limits the maximum force that can be applied and helps to distribute the total force between the different fingers.

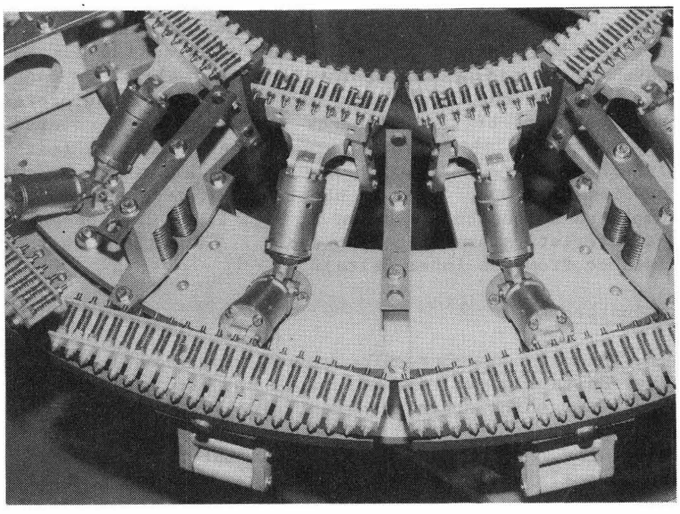

Fig. 3 The pushing-sectors of a short-circuiting plate

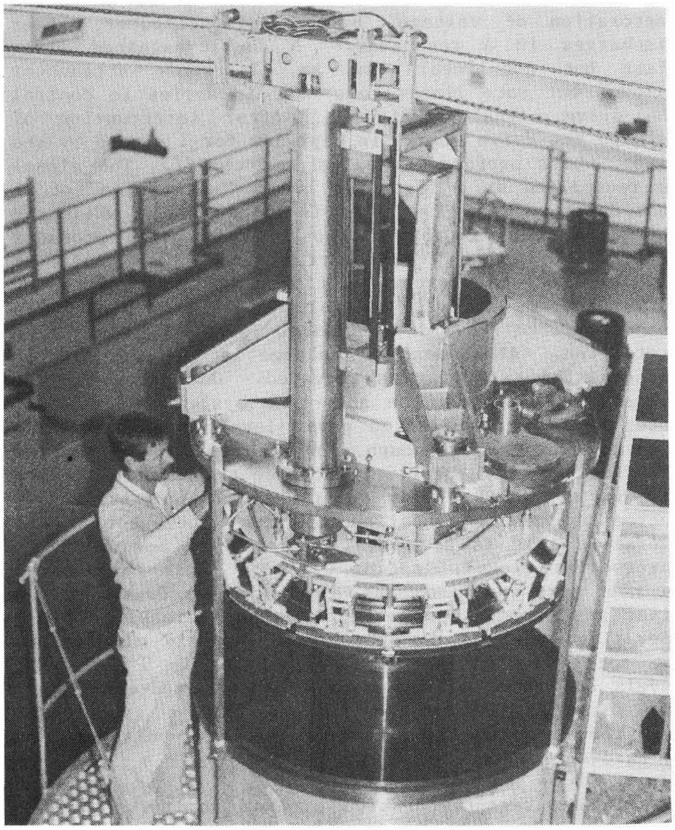

Fig. 4 Installation of a short-circuiting plate

The short-circuiting plate is guided by two sets of 6 polystyrene wheels (350 mm apart) running on the surface of the inner cylinder. This limits tilting of the plate to 4 mm. A short-circuiting plate is positioned along the length of a cylinder by means of a single "push-chain" system. Two identical chains, with links which only allow bending in one direction (from a straight-line position), are used in a back-to-back fashion. Each chain-pair is linked at one end and attached to the short-circuiting plate. The chain system is driven by two sprockets (geared together to move synchronously) using a motor and reduction gearbox. The part of the chain system between the linked end and the sprockets form a rigid section capable of positioning the short-circuiting plate with a maximum force of 400 kg, even when the chains are extended by 2,4 m. A total short-ciruiting assembly weighs 250 kg and the friction force is 70 kg. The outer part of both chains are looped out in opposite directions, each around an idler sprocket as shown in Fig. 1 and 4. The positioning system only occupies 1,5 m outside the cylinders.

A two-stage telescopic-tube system with differential sliding-seals enables the vacuum requirements to be met for the 2,4 m movement. The "push-chain" is located inside the telescopic tubes, but not supported by it. The cooling water, air pressure and electrical signals of the short-circuiting plate are routed along the inside of the telescopic tubes (adjacent to the chain), using flexible poly-ethylene pipes. Additional guidance for the pipes is provided by pulleys next to each of the chain sprockets. The stationary ends of the chains and the pipes are attached to the outer support, thus resulting in a neat system of moving chains and pipes.

For removal of a short-circuiting plate the two inner cylinders of a resonator are bolted together across the gap where the beam particles normally pass through. After bolting the short-circuiting plate to the endplate, the endplate structure can be disconnected from the inner and outer cylinders. On top the assembly is removed by crane, using a single lifting point precisely above the centre of gravity as shown in Fig. 4. At the bottom it is removed by hydraulic platform. The inner cylinders are positioned concentric and parallel to the outer cylinders to better than 0,5 mm and all parts of the short-circuit system have operated reliably, despite the fact that a single positioning system (acting off-centre) is used.

Capacitor units. The two large capacitors of a resonator are identical. One is mounted above and the other below the inner delta. They are trapezoidal in shape (3,5 m by 0,8 m) with 400 mm high sides. The capacitor box is made from 3 mm thick copper plate and cooling pipes are attached on the inside. The effect of the capacitor gap can be seen in table 1. The 380 mm positioning range is provided by 3 lead-screws (coupled by a serrated belt) and vacuum sealing is by 3 flexible bellows. The waterpipes are routed through a fourth bellows. Electrical contact between the capacitor and the copper liner of the vacuum chamber is made by retractable fingers mounted on the outer liner adjacent to the four sides of the capacitor box. The fingers can be withdrawn by four operating rods (each actuated by a pneumatic cylinder) to allow movement of the capacitor without damaging the fingers.

Coupling capacitor. The adjustable coupling capacitor enables optimum power transfer between power amplifier and resonator via the 50 ohm coaxial cable. The plate of the capacitor is 400 mm wide and 300 mm high, with rounded corners and edges. The gap to the back of the inner delta has a range of 30 to 250 mm. The plate is electrically and mechanically connected to the inner conductor of the cable. Electrical insulation and vacuum sealing between the inner and outer conductor is done by means of a glass cylinder and O-rings. Electrical contact between the outer of the cable and the liner of the chamber is by sliding contact-fingers and vacuum sealing is by bellows, fitting over the outer conductor. Positioning is by 3 lead-screws, coupled by a serrated belt, using a stepping-motor and reduction gearbox. The way in which the cable is routed from the hole in the wall of the vault to the coupling capacitor, as shown in Fig. 1 and 2, allows the coupling capacitor to move by flexing of the cable.

Fine-tuning capacitors. Each resonator has two fine-tuning capacitors, located left and right of the coupling capacitor. Each plate is 300 mm high and 560 mm wide. It can be positioned between 20 and 150 mm from the inner delta by a stepping motor using a reduction gearbox and a ball-type lead-screw. Vibration isolation is required for the drive connection and mounting of the stepping motor. Each capacitor plate is connected (along the top and bottom) to the copper liner of the chamber by flat copper braids, placed side by side. The braids are flexible and long enough to allow 130 mm movement. Two capacitors were provided to enable sufficient tuning range at the lowest frequency. For the upper range, one is adequate. In fact the resonator is so stable that only 3 mm movement of one plate is required, for tuning between 5 and 100 kW, at 26 MHz.

Resonator support. Each resonator is accurately supported from brackets, attached to the two adjacent magnets, during normal operation. For maintenance a resonator can be lifted slightly by four hydraulic jacks mounted on a permanently installed trolley and can then be rolled back 3 m. The trolley runs on rails at ground floor level and it is also used to facilitate removal of the bottom capacitor unit.

Resonator maintenance. The inner surfaces of a resonator can be reached after removal of a large capacitor. There is sufficient room for a person between the inner delta and the chamber and between the inner and outer cylinders. It is also possible to remove the top half of a resonator to gain access between the inner delta halves. A frame is bolted to the top plate of the resonator chamber and after removal of the bolts and locating pins, the two hooks of the overhead crane are used to lift the top half (as shown in Fig. 2). It can be moved over the roof beams if required.

Power amplifiers

The two 150 kW power amplifiers are similar to the type developed for long-distance radar applications by the manufacturer. This type is well suited to accelerator use owing to the automatic tuning and remote control facility. A very low noise level is achieved by extensive vibration damping and good supply-frequency filtering (Noise further than 50 Hz from carrier is -80 dB and spurious output is -75 dB). The power amplifiers have three tuned vacuum-tube stages, preceded by two broadband solid-state stages. The amplifiers employ PI-L output matching-networks, which must be properly terminated during automatic tuning. A water-cooled 50 ohm dummy load is used. The procedure is to tune each amplifier in turn with the dummy-load termination, then to switch both to their respective resonators. Load switching is accomplished by means of a remotely-controlled coaxial transfer-switch at each amplifier and at the dummy load. To facilitate remote control of the amplifiers, they are able to receive command signals, and return status signals, via fibre-optic cables. We have interfaced this system to the SSC rf control system. Selected current or voltage values can be returned and the coaxial transfer-switches, mentioned above, can also be controlled via the fibre-optic link.

Control and stabilization

Most of the equipment for phase and amplitude control and stabilization is identical to that which has been in use successfully for the injector cyclotron.[1] Phase signals from the resonator and the coupling capacitor control the automatic fine-tuning of a resonator. This system has a 1° dead-band to avoid unnecessary mechanical movement. During stabilized operation phase variation is ±0,1° and amplitude variation less than 0,1%. Power-limiting is provided as part of the resonator-voltage amplitude-control and stabilization system. All units of the system were developed and constructed at the NAC. A microcomputer (developed by the NAC control group) controls the entire rf system of the SSC, in a very user-friendly manner.[2] Computer control of all equipment was provided right from the start. By means of a mailbox module, as part of the CAMAC system, control is efficiently extended to the main control console.

Operation

Initial experience is described elsewhere.[3] Most objectives have been achieved and the SSC rf system has performed well. The pulse response of an amplifier (1 µsec) is adequate to overcome multipacting in the resonators. The reflected power at the output from the amplifier and the voltage at the coupling capacitor are monitored continuously by fast comparator circuits. As soon as a discharge occurs in a resonator, the drive signal is switched off (response time 2 usec) to avoid damage due to subsequent rf power from the amplifier. The 15 m long power cable between amplifier and resonator did not cause transfer problems at any of the operating frequencies (12,5, 15, 16,4, 18, 22,5 and 26 MHz).

The latest achievement has been fully automatic restoration of voltage, by the microcomputer, after discharges in a resonator. A double-balanced mixer (fast but non-linear) and an electronic attenuator (slower but more linear) are used in series to control the drive signal amplitude. After interruption of voltage the drive signal is kept low for 1 second by the mixer, which performed the fast switch-off. The signal is re-applied as a fast-rise 100 kW "kick-pulse" of 15 µsec duration, when the mixer is opened fully, while the attenuator has low attenuation. This pulse produces sufficient rate of power rise from the amplifier (100 kW/µsec) to overcome multipacting. The subsequent 10 kW sustain level, controlled by the mixer, is necessary to avoid tripping of the amplifier protection. Attainment of voltage is checked, and if unsuccessful, starting is repeated. One second at the sustain level allows the auto-tune system to optimise, after which the reflected power level is checked. As soon as this is low enough, power is increased. During the first part of the power increase the mixer is opened step-wise, until fully open, while simultaneously increasing the attenuation of the attenuator. The overall result is a gradual increase in power, to an intermediate level, lasting 0,5 sec. This change-over is necessary owing to the distortion produced by the mixer at intermediate settings. The increase to final operating level is done by the electronic attenuator. The total time for voltage restoration is 3 sec. All levels and rates of change are under computer control and can easily be optimised for a particular requirement. Only the timing of the "kick-pulse" is set by hardware.

The voltage-restoration program monitors the two resonators alternately. Even on the rare occasion that both resonators trip together, it does not take longer than 6 sec to restore voltage on the SSC. Such quick restoration of power avoids thermal changes in the resonators and allows unattended operation of the resonators even at maximum power, when occasional discharges may occur. For initial start-up slower rates of change are used.

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