PERFORMANCE OF THE NAC RF SYSTEMS

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ABSTRACT

The radio–frequency resonator systems of the NAC cyclotron facility have been in continuous operation for the past two years. Restarting procedures, stabilization, performance and faults are described. The systems have operated at 20 different frequencies in a wide range between 10 and 26 MHz. The two resonators of the k=200 separated–sector cyclotron (SSC) operate reliably at voltages up to 250 kV peak and the two resonators of the k=8 injector cyclotron operate up to 60 kV. The buncher resonator in the transfer beamline operates up to 70 kV, in the 20 to 52 MHz range. The pulse–selector, which reduces the pulse repetition–rate of the beam pulses, is located in the injection chamber of the SSC. Accurate temperature stabilization of the cooling water ensures excellent repeatability. Amplitude and phase stability of all the systems were adequate from the start, using equipment developed at the NAC. Computer control of all functions enables automated operation over long periods, even when repeated spark–over or interruptions occur.

1. INTRODUCTION

The main features of the rf–systems of the injector cyclotron[1], the separated–sector cyclotron[2], buncher and pulse–selector[3] have been described at previous conferences. Performance of these systems over the first two years of full–time operation is reviewed.

2. SUMMARY OF CHARACTERISTICS

The two half–wave resonators of the SSC are coarse–tuned by means of adjustable short–circuiting plates plus capacitor plates. The maximum current density at contacts of the short–circuiting plates is 60 peak Amps/cm. Coarse tuning of the injector's two quarter–wave resonators is by means of short–circuiting plates only, whilst the buncher's single quarter–wave resonator uses only capacitive coarse–tuning. In the pulse selector the coarse tuning is by means of a water–cooled coil. For the injector a sliding tube with differential vacuum seals enables each short–circuiting plate to travel 4 m. A two–tube telescopic system, with similar seals, allows 2.4 m travel for each SSC plate. Water–cooling and control services to the plates run inside the tubes. Vacuum sealing for coarse capacitive tuning is by stainless–steel bellows, permitting up to 380 mm adjustment. All systems use capacitive fine–tuning and capacitive coupling. Copper is used for all rf–conducting surfaces and copper or stainless steel for all resonator vacuum surfaces. The buncher amplifier is mounted directly on its resonator. All other systems use 50–ohm coaxial cable between the amplifier and resonator. The SSC amplifiers are located outside the vault for easy access.

Electrical Characteristics: (per resonator system)

System	SSC	Injector	Buncher	Select
Number of resonators	2	2	1	1
Accelerating gaps	2	2	2	1
Freq. range (MHz)	6–26	9–26	12–52	2–4.4
Peak voltage (kV)	250	60	70	5
Power at pk kV (kW)	100	20	3	0.75
Ampl. noise ($\times 10^{-4}$)	5	10	20	20
Phase noise	0.2°	0.4°	0.2°	0.5°
Maximum Q–value	17000	7000	4000	135
50–Ω coupling cable	15 m	4 m	None	30 m
Max. amp. power (kW)	150	25	10	1

Mechanical and Vacuum Characteristics: (per resonator system)

System	SSC	Injector	Buncher	Select
Resonator weight(kg)	25000	4000	300	50
Chamber volume (m^3)	16	1.5	0.25	8
Pumping speed (l/s)	8000	2500	0.25	20000
Pump–down time (h)	12	4	12	6

3. AMPLITUDE AND PHASE STABILIZATION

Amplitude stabilization for each resonator is performed by an electronic attenuator, controlled by the error signal between the demodulated rf signal from the resonator and a stable reference voltage (under computer control, with 15 bit resolution). The control–loop gain and filtering are under computer control to facilitate loop optimization. Adjustable power–limiting forms part of the amplitude stabilization system and all resonator systems use similar units.

Phase stabilization for the SSC and the injector is performed by the wide–range phase modulator described previously[1]. A new unit had to be developed for the different frequency ranges of the buncher and pulse selector. It is based on a wide–band quadrature hybrid, two electronic attenuators and a combiner. The phase control range is ± 40° over the required frequency range. All rf systems use the same type of phase meter, with a measuring resolution of 0.1° over the full frequency range. The phase control–loop gain and filtering is under computer control.

The resonator is kept on tune by the auto–tune system which uses the phase signal between the resonator and the coupling–capacitor voltage to drive the stepping motor of the fine–tuning capacitor. A dead band of ± 2° is used to prevent continuous operation of the motor. The auto–tune system also provides pre–positioning of the fine–tuning capacitor, before starting resonator operation.

4. CONTROL

Computer control was incorporated into the design of the rf system from the start. The design philosophy was to use a modular system in which each instrument is provided with local memory to retain the last valid instruction, even if communication with the control computer is lost. A common eight–bit data link is used for all instruments associated with a resonator. Each function in an instrument is controlled by an associated strobe line. In a few cases where more than eight–bit accuracy is required, two strobes are used per function to provide up to 16–bit accuracy. 8–bit microcomputers have been used until now, with one microcomputer and its terminal controlling two resonators i.e. one for the injector, one for the SSC and one for the buncher and pulse–selector combined. All 50 variables of a system are stored as a file in the bubble memory of each microcomputer to ensure an extremely reliable data base, with a file for each frequency already used. A file is usually updated at the end of each run at that particular frequency. In addition two identical files are kept in the bubble memory, containing the current condition. This is essential to ensure fault–free recovery after power failures. The two current files are automatically updated every two minutes. This fact combined with the local memory in the equipment ensure an extremely robust control system.

A change in operating frequency is performed by menu selection. All previous conditions are listed in terms of frequency and beam parameters. The choice is made by cursor manipulation and all variables are then set accordingly. Members of the rf–group have access to the control of all variables in order to optimize a system. Preset and incremental control is provided. Procedures were provided to automate operation as much as possible.

The cyclotron operators have limited control of the rf system. In addition to stopping and starting, only incremental control of resonator voltage and phase is allowed. Regular readback of important system values is provided above the space reserved for fault reports, on the same control page. Incremental phase control is performed by a vernier phase–shifter in combination with a switching–type binary phase–shifter. The computer combines the control of the two units to appear as one phase variable to the operator. Phase changes can be done at full power on all systems. When necessary a procedure can be selected to centre a phase modulator at the centre of its control range. The rf voltage of the injector is switched off for fast equipment and personnel protection until the faraday cups in the injector beamline have operated. The rf voltage is restored automatically before significant thermal changes occur. Restarting is so reliable that this facility, which operates frequently, does not cause any operational delays.

5. PERFORMANCE

5.1. Restarting Resonator Voltage

It is essential that a resonator is correctly tuned before attempting to restart the rf voltage. Owing to the excellent mechanical stability and repeatability of the resonators and the fact that the cooling–water temperature is stabilized to 0.1 °C, restarting can usually be done by repeating previous conditions when repeating a frequency. When an SSC resonator is switched off, after operation at high power, the resonant frequency follows a cool–down curve. An approximation of this is used to predict the fine–tuning position during the first 10 minutes after switch–off. For longer off times the cold position is adequate. At frequencies where no previous data exist, resonance is determined at very low power by watching a sensitive oscilloscope while fine–tuning manually.

Tuning of the injector resonators is significantly influenced by the position of the ion–source. If it is accurately repeated at a frequency–change, restarting is successful without manual tuning. During operation the best method for restarting rf–voltage is to measure and update the actual fine–tune position every 10 seconds and to use this as the tune starting point. An adjustable tune–position off–set, in the cool–down direction, is used by the program. Restarting is attempted in four steps over the off–set range. In most cases success is achieved on the first or second step. The above procedure follows the repositioning of the ion source during beam optimization, to ensure reliable restarting after a discharge or a switch–off condition.

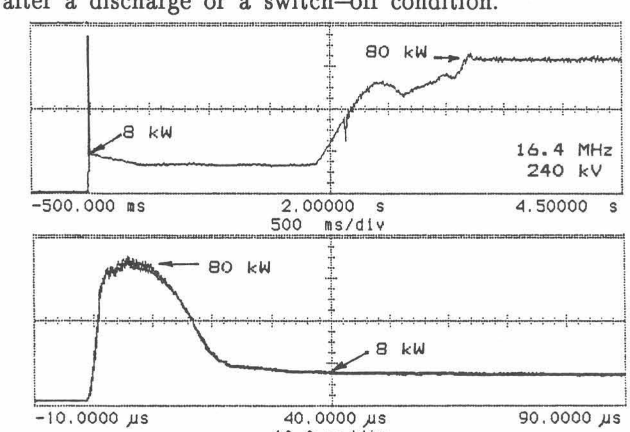

Figure 1: Power variation with time while starting SSC resonator operation. The expanded bottom trace shows the "kick–pulse".

The "kick–pulse" starting method, described previously[2], was developed to overcome multipacting problems. Initially, particularly at 26 MHz, the problem was severe, aggravated by the strong magnetic field. At present reliable restarting is ensured by operating with tighter coupling than that giving minimum reflected power. At the carefully determined operating point it is possible to have reliable restarting and operation at maximum voltage without re–adjustment of the coupling capacitor. The "kick–start" facility was provided for all resonator systems to ensure reliable restarting.

5.2. Operation

5.2.1. Separated–sector cyclotron

Lost beam time per annum due to SSC rf faults fell from 98 hours during 1987 to 39 hours during 1988, indicative of the excellent present performance. The phase and amplitude stability helps to enable the 99.8% transmission through the SSC, which is regularly achieved with a 60 microamp proton beam current at 66 MeV. The smallest voltage step provided by the control system is 10 V in 250 kV. Conditions can be repeated with this resolution, thus confirming the long–term stability and low noise level. Phase control resolution is 0.05° with a medium–term variation of 0.2°.

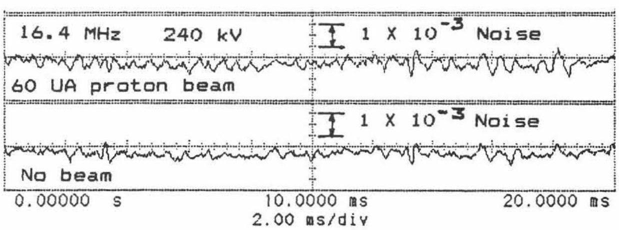

Figure 2: SSC voltage–amplitude noise during one 50 Hz cycle. The bottom trace is without beam current and the top is with 60 μA.

Frequency changes normally occur twice weekly. A resonator frequency change is fully automated, requiring less than 15 minutes. It is usually possible to have the rf started and operating at the required level before the magnetic field has stabilized. The short–circuiting plate positioning mechanisms have been reliable. The same applies to the retractable contact fingers of the SSC coarse–tuning capacitors and short–circuiting plates.

The amplifiers have performed well, using the local–control tuning mode and re–tuning is seldom necessary between frequency changes. The remote–control tuning does not yet have the same reliability for 24–hour–a–day operation. None of the water–cooled power tetrodes have had to be replaced during 16000 hours of operation. The 15 m length of 50–ohm coupling–cable has not given resonance problems at any of the frequencies used. Variation in amplifier gain with ambient temperature is compensated for by computer adjustment to retain a constant 20% power reserve. Phase and amplitude loop errors are regularly updated on the display and the amplitude errors are displayed on an oscilloscope in the control–room. Operation is mostly in the 200 to 240 kV range and usually many hours pass without need for re–adjustment.

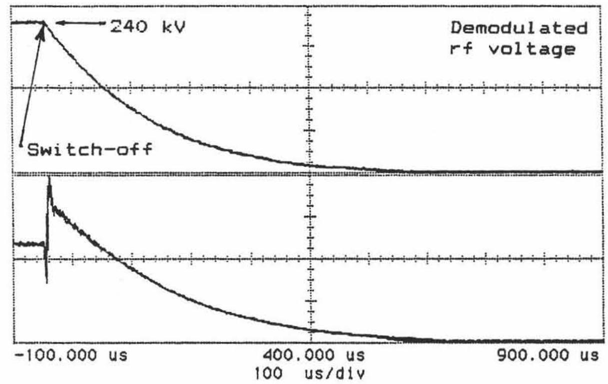

Figure 3: Smooth decay of the SSC resonator's voltage at 16.4 MHz indicate low multipacting level as shown at the top. The associated coupling–capacitor voltage is at the bottom.

5.2.2. Injector cyclotron

Lost beam time per annum due to injector rf failure decreased from 118 hours during 1987 to only 10 hours during 1988, underscoring the present very satisfactory performance. Mechanically the resonators are not as rigid as those of the SSC or the buncher. A small amount of capacitive coupling exist between the two injector resonators, making phase stability more difficult, and requiring both resonators to be stopped and started simultaneously. The 6 mm spacing between ion–source and puller results in high voltage–gradients and consequently discharges can occur fairly frequently during operation at high voltage. The handling of the ion source makes a significant difference in the high–voltage conditioning time required. The vacuum pump produces a 2° peak–to–peak phase noise on the resonators, which is reduced sufficiently by the phase stabilization system to result in good long–term stability, reliability and repeatability. The short–circuiting plates are reliable. Frequency changing is fully automated, taking 10 minutes.

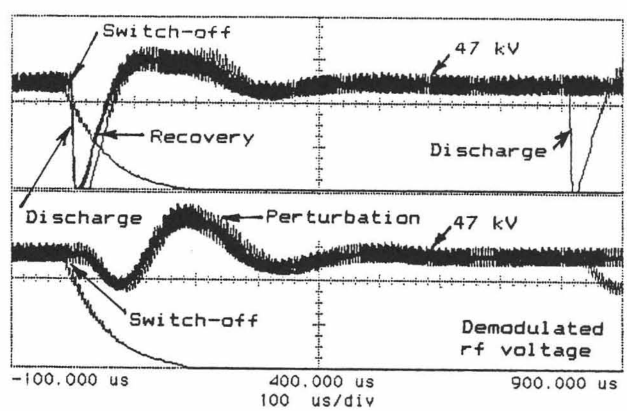

Figure 4: The simultaneous smooth voltage decay of the injector's resonators, after power switch–off, indicate low multipacting level at 16.4 MHz. The darker overlay shows recovery after occasional discharges in one resonator and the associated perturbation produced in the other resonator through capacitive leakage coupling.

5.2.3. Buncher

The buncher is located midway along the

beamline between the injector and the SSC. Lost beam time due to buncher faults increased from 10 hours during 1987 to 46 hours during 1988, as a result of faults encountered when going to higher voltages. Since the necessary improvements were made, operation at high level has been reliable. The functions of coupling and fine–tuning were combined in one unit from the design stage[3]. This has been worthwhile and confirmed the expectation that a separate fine–tuning capacitor is unnecessary. Contact fingers of the two coarse–tuning capacitors have operated reliably and their sliding action enables tuning to be optimized at normal power level. The driver and power amplifiers, constructed at the NAC, have performed well. Restarting of resonator voltage is easy and multipacting only occurs below 8 kV resonator voltage.

5.2.4. Pulse selector

The selector is only required for neutron time–of–flight experiments and it has been used at two beam energies. Operating conditions are listed below.

Proton beam energy (MeV)	66	126
Selection factor	5	6
Select. freq. (MHz)	3.275	3.612
Peak rf voltage (V)	1000	2000
rf power (W)	20	100

The system performs reliably and is easy to operate. No multipacting has been encountered. The deflection plates are positioned 40 mm apart for selector operation and 110 mm apart for high current operation, when the selector is not required. Total resonator capacitance is 165 pF as a result of rf shielding required around the 1.5 m long plate and feeder line. Availability of a beam–diagnostic harp, just beyond the adjustable collimating slit of the selector, provides for an easy method to optimize phase and voltage of the selector.

6. FAULTS AND MAINTENANCE

Ease of maintenance was given high priority from the design stage of all rf systems. On the SSC it has been put to test on three occasions. Firstly a turbo–molecular vacuum–pump disintegrated, scattering aluminium pieces into one resonator. The bottom coarse–tuning capacitor was removed to gain access to the resonator for cleaning. The total time taken, excluding venting and evacuation, was only eight hours. Secondly, during scheduled maintenance at the end of 1987, a water leak developed in the first extraction magnet, which is mounted inside the inner delta of one resonator. This required the top half of the resonator to be removed through the SSC roof, after rolling the resonator from its position between two sector magnets, on the maintenance trolley. Eight hours was sufficient for removal and the same for re–assembly. Some soft–soldered contact–fingers, used between the side walls and the top and bottom plates of the resonator chamber, were dislodged during this opening of the resonator and one area showed signs of overheating. All faulty fingers had to be replaced by contact–strips, made from dispersion–strengthened copper. Thirdly, during March 1989 tripping occurred frequently in the same resonator, while going from low to high power. Operation at normal level was still reliable but poor contact of the contact–strips was suspected. During a maintenance weekend the top coarse–tuning capacitor was removed. A few contact–strips had slipped out of position at the joint between the back wall and the bottom plate, causing arc–over at one spot. The faulty strips were replaced by ones with locating lips, to prevent recurrence. Total repair–time, including venting and evacuation was 48 hours.

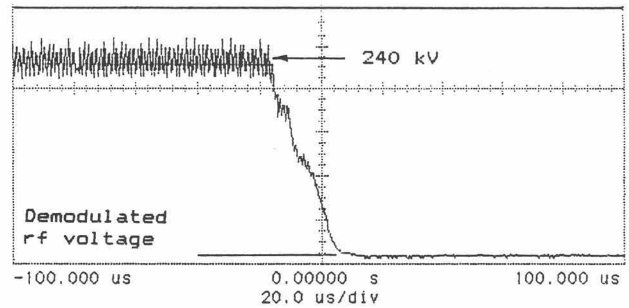

Figure 5: SSC resonator voltage collapse at 16.4 MHz, caused by arc–over at faulty contact strips.

The major mechanical maintenance needed for all resonators and amplifiers is lubrication of drives required for frequency–changing elements and lubrication of sliding vacuum–seals. The most major electrical repair of the SSC and injector rf amplifiers to date was replacement of high–voltage rectifiers in power supplies as a result of overvoltage surges.

The buncher was designed and constructed within a year, but after a year's operation the coupling–system feedthrough–insulator required improvement to decrease voltage gradients. Initially not all edges were sufficiently rounded. This teflon insulator was enlarged, and at the same time the coupling capacitor plate was electrically joined to the anode connection, using sliding contact fingers. This cured the discharge problem but the change in geometry resulted in a spurious 109 MHz oscillation in the amplifier. The insertion of a water–cooled damping resistor at the anode connection has since restored reliable operation.

ACKNOWLEDGEMENTS

The following persons contributed to the excellent performance of the rf systems: J.E.Kriel was responsible for voltage–restoration, protection and stabilization systems, J.W.Carstens for power amplifiers and their remote control while R.K.Fisch wrote the control programs. A.Kiefer helped with mechanical repair of the resonators.

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