PULSE SELECTION AND REBUNCHING IN THE NAC TRANSFER BEAMLINE

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Summary. The design and construction of a rebuncher, located approximately halfway between the light ion injector cyclotron and the separated-sector cyclotron (SSC) of the NAC, is discussed. A pulse selector, necessary to provide a longer time interval between beam pulses (required for neutron time-of-flight experiments), is described.

Introduction

The NAC separated-sector cyclotron (SSC) is a variable-energy light and heavy ion accelerator, to be used for nuclear research, isotope production and medical therapy.[1] Its maximum design energy is 200 MeV for protons at a resonator frequency of 26 MHz, operating on harmonic number h=4. At lower energy and for the acceleration of heavier ions harmonic numbers h=4 and h=12 will be used (the minimum rf frequency is 6 MHz). Beams of light ions are injected into the SSC through a transfer beamline connected to a k=8 solid-pole injector cyclotron SPC1. It is planned to add a second injector cyclotron SPC2, which will accelerate heavy ions and polarized protons and deuterons from external ECR and polarized ion sources, respectively[2].

To obtain single-turn beam extraction from the SSC, the longitudinal spread of an 8 MeV proton beam pulse should not exceed 8° in rf phase at injection. The inherent phase spread in SPC1 beams is larger than this, and the energy spread (typically one part in 750) further increases the beam phase length as the beam travels along the 25 m long line. A beam rebunching system is therefore essential in the transfer line from SPC1, as well as in the future line from SPC2. The first part of this paper describes the design and construction of a rebunching system, located approximately halfway along the transfer line between SPC1 and the SSC.

For neutron time-of-flight measurements, the time interval between ion beam pulses ideally needs to be as long as 800 ns. As this may be as high as 20 times the pulse repetition time of some ion beams at their highest energy, a mechanism is required for the removal of some of the beam pulses prior to their final acceleration. The second part of this paper describes an inexpensive pulse selection system, which will be situated at the entrance to the injection valley chamber of the SSC.

Rebuncher Design

The rebuncher consists of two accelerating/decelerating gaps separated by a drift tube, and operates at the second harmonic of the cyclotron's resonator frequency. The design of the rebuncher and the determination of its operating parameters have been made by considering the effect of the rebuncher on the longitudinal phase space of particles in the transfer beamline. An optimally bunched beam is considered to be a beam in which an upright phase ellipse in longitudinal $(\Delta\phi, \Delta E)$ phase space at the exit of SPC1 is mapped by the transfer matrix in longitudinal phase space, for the particular rebunching arrangement, onto an upright phase ellipse at the injection valley of the SSC (for this purpose the required radial-longitudinal injection matching is neglected, as it can always be effected by other transport elements). The requirements for the transfer line can be expressed in terms of its transfer matrix and lead to a beam-independent bunching parameter P, which yields the buncher voltage amplitude V_0 for a specific beam as:

$$V_0 = P\frac{E}{Q}$$

with E and Q the ion's energy and charge number respectively.

The transfer beam line between SPC1 and the SSC has been designed with one rebuncher placed at 10 m along the 25 m long line. Calculated values of the optimum voltages are displayed in Table 1 for ranges of the input parameters in longitudinal space, at two proton energies. Owing to the placement of the buncher in the first half of the transfer line, no nett bunching is available, i.e. the final ratio of $\Delta\phi/\Delta E$ is always larger than the initial ratio.

Table 1 Summary of rebuncher parameters

SPC1 Beam		Rebuncher voltage V_o (kV)		SSC Beam	
Relative energy spread	phase spread (rf deg)	E_p=3.1MeV (66 MeV)	E_p=8.0MeV (200 MeV)	Relative energy spread	phase spread (rf deg)
2.000×10^{-3}	12°	23.5	60.5	6.369×10^{-3}	3.8°
2.000×10^{-3}	15°	23.8	61.5	8.000×10^{-3}	3.8°
2.000×10^{-3}	18°	24.0	61.9	1.000×10^{-2}	3.6°
2.000×10^{-3}	21°	24.1	62.2	1.136×10^{-2}	3.7°
1.333×10^{-3}	12°	24.0	61.9	6.667×10^{-3}	2.4°
1.333×10^{-3}	15°	24.1	62.3	8.197×10^{-3}	2.4°
1.333×10^{-3}	18°	24.2	62.4	1.000×10^{-2}	2.4°
1.333×10^{-3}	21°	24.3	62.6	1.111×10^{-2}	2.5°
1.000×10^{-3}	12°	24.1	62.3	6.452×10^{-3}	1.8°
1.000×10^{-3}	15°	24.2	62.5	8.065×10^{-3}	1.9°
1.000×10^{-3}	18°	24.2	62.7	1.000×10^{-2}	1.9°
1.000×10^{-3}	21°	24.3	62.7	1.124×10^{-2}	1.9°

The optimum rebunching parameters of the beamline to SPC2 have been obtained, although this line still has to be designed finally. The additional line (length ~36 m), which joins to the SPC1 transfer line, requires only one rebuncher. The two rebunchers in the line from SPC2 are assumed to be identical, also with respect to the applied voltages.

Rebuncher resonator

Electrical Design

A quarter-wave coaxial resonator of fixed length, with frequency adjustment by means of two capacitor plates, was chosen as the most suitable system for the 12 to 52 MHz band. Maximum power dissipation occurs at the highest frequency. The voltage gradient in the capacitor gap is a limiting factor at low frequencies. The design, which included optimization of the capacitor area and inner conductor diameter, made provision for 156 kV peak rf voltage at 52 MHz (allowing for the poorest beam quality). Recent measurements of the actual beam quality indicated that a much lower voltage (63 kV) will normally be required. The characteristics of the rebunching resonator are given in Table 2.

Table 2
Characteristics of the rebuncher resonator

Frequency (MHz)	Voltage (kV)	Power (W)	Gradient (kV/cm)	Gap (mm)
12	8.3	466	27.9	3.0
22	27.9	2003	24.6	11.3
32	59.1	4880	20.5	28.8
42	101.8	8931	14.8	68.9
52	156.0	13680	7.8	200.0

Mechanical Design

The rebunching tube is 325 mm long with a 52 mm diameter hole and a 50 mm gap on each end. It is part of a copper box (325 x 450 x 100 mm) connected to the 76 mm diameter inner conductor, which is welded to the circular short-circuiting plate. This in turn is bolted to the flange of the outer conductor, which is welded to the outer chamber (enclosing the box electrode). The copper chamber and outer conductor are shown in Fig. 1. The

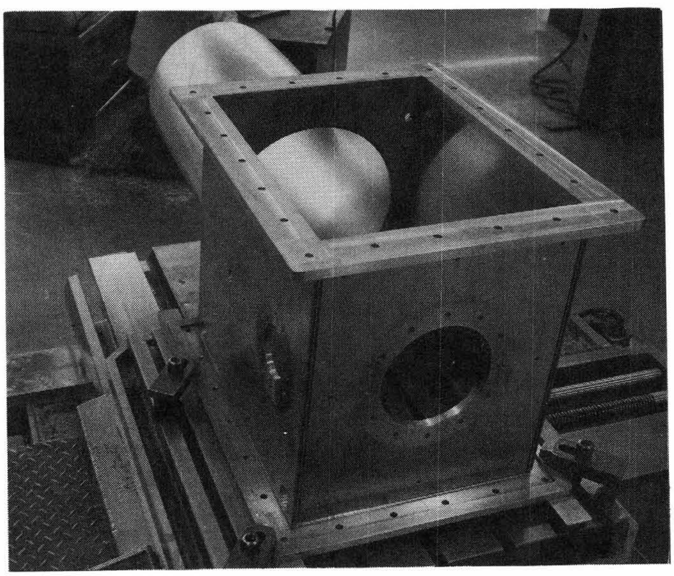

Fig. 1 Chamber and outer conductor of the rebuncher

beam particles enter and leave through holes in opposite sides of the chamber. Two water-cooled capacitor boxes, made from 3 mm thick copper plate, are mounted in the chamber through the two large rectangular apertures on opposite sides of the chamber. Each rectangular capacitor box is positioned by a lead-screw and guide system. A stainless-steel box, bolted over each rectangular aperture, provides a vacuum-tight enclosure and supports the guide system of the capacitor box. The gap between each capacitor box and the inner box electrode is adjustable over the range 2 to 200 mm, thus providing the required capacitance variation. The common area forming the capacitance is 325 by 400 mm. Flexible bellows provide vacuum sealing for the moving parts. The cooling pipes of the capacitor box are routed through the bellows. A spiral cooling channel is provided on the inside of the inner conductor to allow for 6 Watt/cm^2. The total length of the inner part is 1.05 m. Holes are provided in the chamber for a voltage probe and for viewing.

Electrical contact between each capacitor box and the copper chamber is provided by four rows of contact fingers, mounted on the chamber next to the side of each rectangular hole. The fingers are punched from 0.25 mm thick dispersion-strengthened copper sheet and are assembled by sliding them over a copper cooling pipe (flattened to 3 mm). Copper spacers are used between adjacent fingers to give a pitch of 4 mm. Each finger makes good thermal contact with the cooling pipe after positioning. The four rows of fingers are cooled in series and brackets position them on the copper chamber. One end of each finger is pressed against the wall of the chamber and the other end presses against the side of the capacitor box to make electrical contact across the 30 mm gap. The spring pressure of a finger against the capacitor (25 g) allows sliding contact for movement of the capacitor box. A test assembly was used to investigate the mechanical operation of the fingers in vacuum. Wear due to friction was found to be much more in vacuum than in air, but still acceptable. A thin layer of graphite on the surface of the copper plate gave substantial improvement and allowed 2500 cycles of 150 mm stroke (representing many years of normal operation) with minimal wear. The finger assemblies can easily be replaced and no welding or soldering of the fingers is used. The maximum current density at the sliding contacts is 15 A/cm (6 A per finger).

Coupling capacitor

The functions of coupling and fine tuning are combined in a single capacitor, near the accelerating electrode of the rebuncher, on the side opposite the transmission line. The coupling function requires a capacitance range of 3 to 10 pF. The capacitor plate (200 by 95 mm) is carried on a stem which is positioned by means of a stepping motor via a ball-type lead-screw. The stem passes through a tube, to form a concentric capacitor of 60 pF, which serves as an rf coupling and dc block between the anode of the power amplifier and the coupling capacitor itself. The copper tube also forms part of the vacuum interface through which the coupling capacitor must operate. Stainless steel bellows at the back of the capacitor stem allow the necessary movement. With this arrangement there are no bellows or sliding contacts in the rf path.

Rebuncher power amplifier

This was designed at the NAC to deliver up to 15 kW, in the band 12 to 52 MHz. It is now in the construction stage (Fig.2). The amplifier cabinet mounts directly on top of the rebuncher, with the coupling capacitor forming an integral part of it. A water-cooled tetrode is used

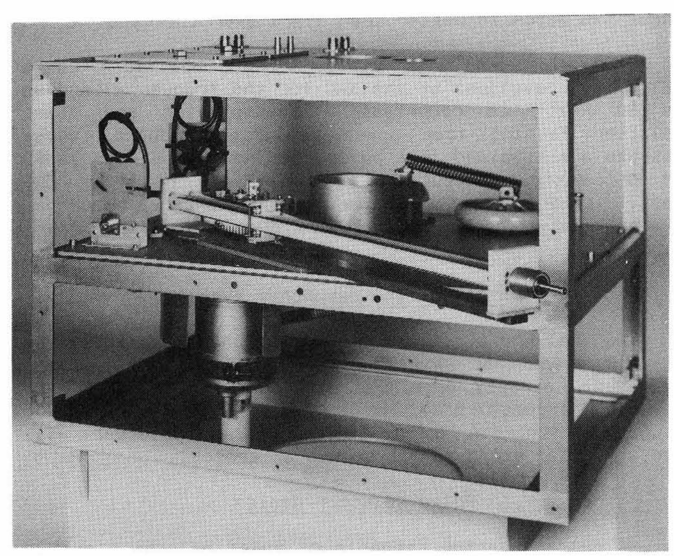

Fig. 2 Power amplifier for the rebuncher

in grounded-cathode configuration. The nominal load impedance is 650 ohms but this will vary slightly as the rebuncher's auto-tune loop operates, due to the dual function of the coupling capacitor. The amplitude controller will compensate for perturbations in gain when the capacitor is moved slightly during fine tuning. The 6 kV anode supply is decoupled from the rf voltage by a two-stage filter. The first section is formed by a choke connected at one end to the anode and at the other to a 1200 pF feedthrough capacitor. The choke, measuring 7 μH at low frequencies, was optimized to present an acceptable reactance at the anode over the whole band, to avoid switching. A 2.5 μH choke and a 3000 pF disc capacitor form the second section. The screen grid is grounded by means of a 5.6 nF capacitor made from two layers of double-sided printed-circuit board, thus avoiding the resonance often encountered in multiple capacitor arrangements.

The input network is effectively a symmetrical π-network, where a variable inductor forms the series element. The input capacitance of the tube forms the output element and a fixed capacitor is used as the input element. Compared to parallel tuning, it is easier to obtain the required minimum value and range for the inductance. The network is terminated by a 50 ohm load resistor via a 4:1 transformer, thus the grid damping resistance is 200 ohm. A similar transformer at the input matches the 200 ohm network to the 50 ohm feeder from the driver amplifier (situated remotely). For the variable inductor four 6 mm tubes are arranged as two mutually-coupled parallel-conductor transmission lines. Each has a movable short-circuiting roller, machined to make a "v" contact with the tubes. The transmission lines are interconnected to form in effect a two-turn rectangular coil. By moving the short-circuits, the turn size is varied. The residual inductance of this arrangement is small. The measured inductance of the coupled transmission lines at 12 MHz is 1.63μH. The 4:1 transformers are transmission-line types wound with 60 cm of 93 ohm coaxial cable on 60 mm diameter ferrite toroids. One end of the inner conductor is connected to the other end of the outer to form the low impedance point, as in the conventional 4:1 unbalanced transmission-line transformer, but we have made the connection via a second 60 cm length of coaxial cable to compensate for the delay in the winding. Because this compensating winding supports no rf voltage across its shield, no core is necessary. When terminated in 50 ohms, the input impedance deviates by less than 5 ohms from the nominal 200 ohms over the whole band with a phase angle of less than 10 degrees. They have been tested with a throughput of 1 kW at 26 MHz with no significant heating. With the tube in place, the cold input SWR match is better than 1.2:1 over the band.

The wideband solid state driver amplifier, using FET's, was developed at the NAC for the frequency band up to 60 MHz. It comprises a preamplifier and power splitter feeding four power amplifier modules, whose outputs are combined in a power combiner. The gain is 60 dB and maximum output is conservatively rated at 500 Watt. Only four components of the entire rebuncher system need mechanical adjustment over the 12 to 52 MHz band.

Control of the rebuncher system

Control and stabilization of the phase and amplitude of the rebuncher system is performed by standard equipment, already developed for the 6 to 26 MHz band, before frequency doubling. The phase and amplitude detectors function up to 60MHz. The rebuncher will operate under standard microcomputer control.

Pulse selector design

A pulse selector, capable of pulse selection over a wide energy range, will eventually be installed in the low-energy injection line of the future injector SPC2. In the meantime a reasonably inexpensive selection system has been designed to be installed in the existing beamline from SPC1 to the SSC.

Several systems have been considered for the purpose of pulse selection. The most suitable operates in the following way: An alternating voltage is applied to a pair of planar electrodes lying along the beam direction. The resultant vertically transverse oscillating electric field is adjusted to deflect all unwanted pulses and allow only wanted pulses to be accepted by a narrow slit, after a drift space has been traversed to obtain separation. The alternating voltage is of the form:

$$V = V_1 - V_0 \cos(\frac{\omega t}{h} + \phi)$$

with ω the angular pulse repetition frequency and h the pulse selection factor, i.e. one in h pulses is selected. The phase ϕ represents the adjustable phase of the selector with respect to the cyclotron resonators. The two voltages V_0 and V_1 are determined by the conditions that the h-th pulse is undeflected and that the leading ions in the (h+1)-th pulse are only just rejected.

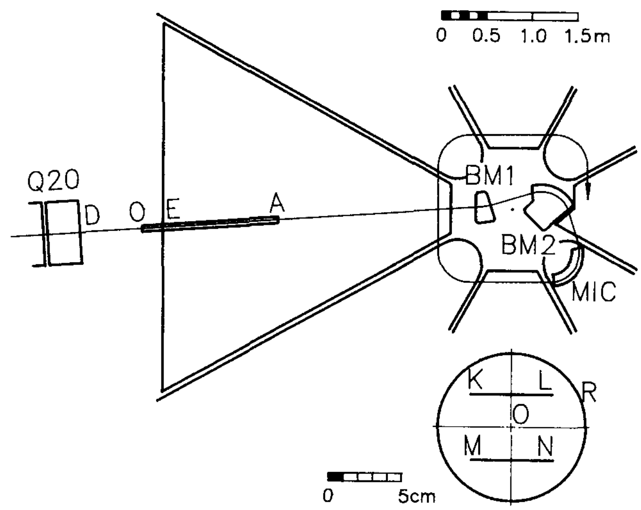

Fig. 3 Schematic drawing of the injection valley chamber and central area of the SSC. The pulse selector is positioned at OA. The cross-sectional drawing shows the upper electrode KL and lower electrode MN of the selector.

The most suitable position (see Fig. 3) for the pulse selector has been found to be at the entrance to the injection valley chamber of the SSC, since the beam travel through the vacuum chamber itself provides adequate drift space for the deflection of unwanted beam pulses. Unfortunately this does entail that the pulse selector has to project some way into the valley chamber and that it is crossed by many turns of the beam during the final stage of its acceleration. An analysis, using the beam orbit program to determine the effect of the pulse deflector on accelerated beams, has shown that resonant excitations of the particle oscillations by the periodically applied selection voltage cannot occur for the beam selection rates envisaged, and that beam heights would typically increase by not more than 0.6 mm. The selector operating conditions for light ions are given in Fig. 4.

Pulse selector deflection system

The bottom deflecting plate is electrically grounded, 1500 mm long and 200 mm wide. The 60 mm wide top plate is supported from above by two insulators mounted on the copper channel forming an rf-shield and support structure. The combined rf and dc bias voltage is applied to the top plate using a shielded connection and a high-voltage feed-through (mounted on top of the vacuum chamber). The cooling water pipes for the top plate provide this electrical connection. The operational gap is 40 mm. The plates can be withdrawn to enable a maximum gap of 115 mm when the deflecting system is not in use and the beam current is large. Construction of this system has nearly been completed.

Pulse selector resonance circuit

Tests showed that a variable inductor in resonance with the 50 pF capacitance of the deflecting plate, is the most suitable method of producing the necessary deflecting voltage in the 2.8 to 7.8 MHz band. The variable-inductor system (8 to 62.5μH) developed on this basis is shown in Fig. 5. Maximum power (300 Watt) is required at 3.716 MHz to produce 11.25 kV peak rf voltage. The Q-value (280) is nearly constant over the frequency range. The inductor is wound on a 250 mm diameter insulating cylinder (having a machined spiral groove), with 26 turns, using 4.8 mm diameter copper pipe. The coil is watercooled and the inductor is insulated from ground to enable 12 kV dc bias to be applied. The bottom end of the inductor is connected to the high-voltage deflecting plate. A copper cylinder 150 mm high is positioned around the coil by 6 guide wheels. The bottom set of 3 wheels are guided between adjacent turns. A contact finger is mounted next to each of these 3 wheels. The three fingers make contact on a single turn of the coil. Friction drive is used to rotate the copper cylinder (by stepping motor and reduction gearbox) thus changing the inductance. Fifteen revolutions provide the required range. The copper cylinder shields the unused part of the inductor and the rf current flows to ground through a 3000 pF disk capacitor shown on the left. The bias voltage for the deflecting plate is applied to the contact finger, installed between the capacitor and the copper cylinder. The circular plates of the remotely adjustable coupling capacitor (8 to 17 pF) are shown on the right-hand side.

The normal signal of the rf system is amplified and clipped to provide a signal, suitable for a standard programmable dividing circuit. The output is buffered to drive a 50 ohm load. Two 9th order low-pass filters follow. One, with 8 MHz cut-off, is permanently in circuit and the other (5 MHz) is switchable. The output signal is suitable for the control and stabilization of its phase and amplitude by standard units, developed at the NAC. These units operate satisfactorily down to 2.8 MHz. The frequency divider and stabilization systems are controlled by computer in a manner identical to the other rf systems. A distributed amplifier with 1 kW capability over the 2 to 27 MHz range drives the resonance cicuit using a 50 ohm cable. The system has been tested successfully with a substitute capacitive load and will be installed as soon as the deflecting-plate system is complete.

References

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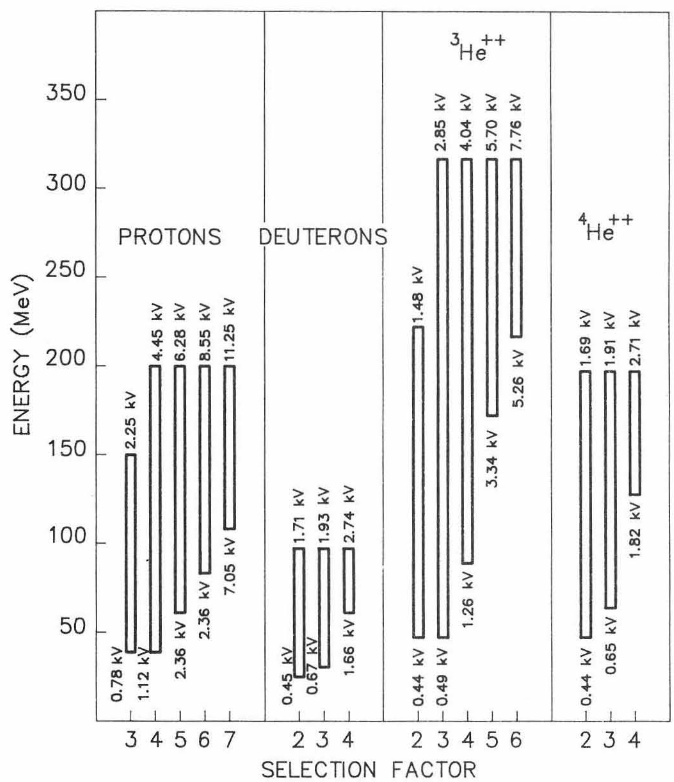

Fig. 4 Bar charts represent for protons, deuterons, $^3H_e^{++}$ ions and α particles, the available SSC energy range as a function of the pulse selection factor h. For each energy range the respective extreme voltage amplitudes V_0 (in kV) are printed at the bottom and top of the bars.

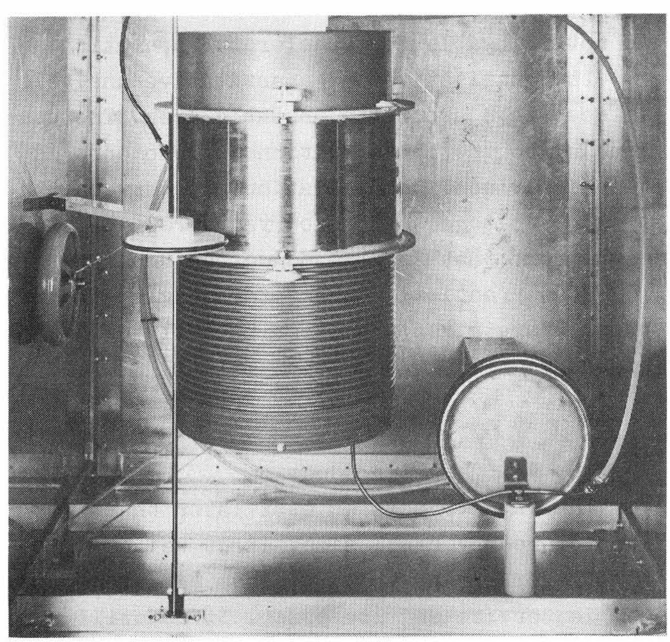

Fig. 5 Pulse selector coupling and inductor system.