PROGRESS WITH NEW BEAMS AND FACILITIES AT NAC

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We report on progress with the development of new beams and facilities at the National Accelerator Centre (NAC), as well as the implementation of a demanding new operation schedule with nine energy changes per week. The following aspects are discussed in more detail: new heavy-ion beams, improvements to our polarized ion source, better beam matching to the isocentric neutron therapy system and the K600 spectrometer, and full operation of the distributed cyclotron control system. Some perspectives for future development are given.

1 Introduction

The NAC cyclotron facilities have been described previously [1] and have run twenty-four hours a day, seven days a week for many years. In contrast to some other particle accelerators of a similar kind, where new areas of research are implemented and applications added in an attempt to survive in a rapidly changing science environment, we have the advantage that NAC was planned as a multi- and inter-disciplinary facility from the outset. Sometimes our facilities are even regarded as a role-model in this context, but as user-demand for more and better beams increases rapidly, it also becomes more difficult to satisfy all requirements, while resources for operating, maintaining and developing the cyclotrons become increasingly scarce. The following sections of this paper give an account of our attempts to cope within this scenario.

2 Cyclotron Operation

NAC operates a separated-sector cyclotron (SSC) and two solid-pole injector cyclotrons – SPC1 for light ions and SPC2 for heavy ions as well as polarized protons and deuterons. Beams are now provided for proton therapy at 200 MeV on 4 days per week, for neutron therapy as well as isotope production with 66 MeV protons on 3 days and 4 nights per week, and for nuclear physics research over weekends. To accomplish this tight schedule requires at least nine energy changes. Hence, beam-time for each application is severely restricted and the highest possible beam currents have to be used for isotope production.

A modified operation schedule with four (instead of three) energy changes per week was introduced in April 1996 to accommodate a second proton therapy shift, and in August 1996 this was then altered to the present schedule which is illustrated in figure 1. Only three hours are made available for each energy change, but actually we average about two hours for routine changes between the 66 MeV and 200 MeV proton beams. The new field setting procedures for the sector magnets, together with better utilisation of the improved control system and more experience gained by the operators, were the main reasons for achieving this. Energy changes before the weekend can take longer, however, because nuclear physics often requires beams at new energies.

The performance of the NAC cyclotrons after more than ten years in operation is still impressive, as can be seen from table 1. Although 1997 was the first full year of operation with the new schedule, beam time still amounted to 77.3% of the scheduled time, while energy changes took 11.1%. Three weekends, set aside for development to decrease the power consumption by using different coil settings for the sector magnets, were cut short by serious leaks in the SSC. Twice our second septum magnet and once our magnetic inflection channel developed water leaks, resulting in increased losses due

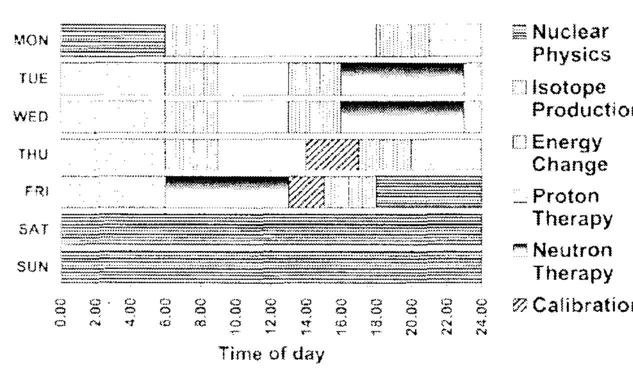

Figure 1: Present weekly cyclotron operation schedule.

Table 1: Operational statistics for the past ten years.

Year	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Scheduled time as % of calendar time	77.9	82.8	85.1	86.4	87.0	87.6	87.4	88.0	89.1	87.5
Scheduled time (hours)	6840	7251	7453	7567	7642	7672	7653	7707	7829	7663
Normalised to 100 %	100	100	100	100	100	100	100	100	100	100
Interruptions (%)	6.4	4.3	6.9	3.9	4.4	5.2	5.3	6.4	6.9	9.6
Tuning beam after power failure (%)	3.8	2.5	0.6	0.8	0.4	0.5	2.9	2.0	2.0	1.0
Beam development (%)	4.0	4.7	3.6	2.2	6.2	1.6	2.1	2.1	3.0	0.8
Energy changes (%)	13.0	5.4	5.5	4.7	5.0	5.7	4.8	5.7	9.3	11.1
Beam tuning (%)	6.9	2.4	0.8	1.6	1.5	0.6	0.9	0.9	0.6	0.2
Beam time (%)	65.9	80.6	82.5	86.8	82.5	86.4	84.0	82.9	78.2	77.3
No. of 8 hour shifts per month	46.9	61	64.1	68.4	65.6	69.1	67	66.6	63.7	61.7

to interruptions. Also the fact that the "uninterruptable" power supply (UPS) has not been operational at all since 1996 contributed more time losses due to power failures. However, tuning improved considerably.

Of our two injectors [2,3], SPC1 is almost exclusively used for the routine applications during the week, whereas SPC2 is mostly needed over weekends for nuclear physics research. The more exotic SPC2 beams are therefore developed during the week so that they are ready on Friday, while SPC1 may be attended to on weekends if necessary. In emergencies, SPC2 has been used to stand in for the therapy applications of SPC1. In SPC1 the problem of melting a hole in the top pole liner above the internal ion-source/puller assembly was solved by re-designing the cooling channels inside the puller. This problem may be ascribed to electron emission from an overheated puller slit – due to the higher currents now used regularly – starting an arc discharge between the puller and the pole liner.

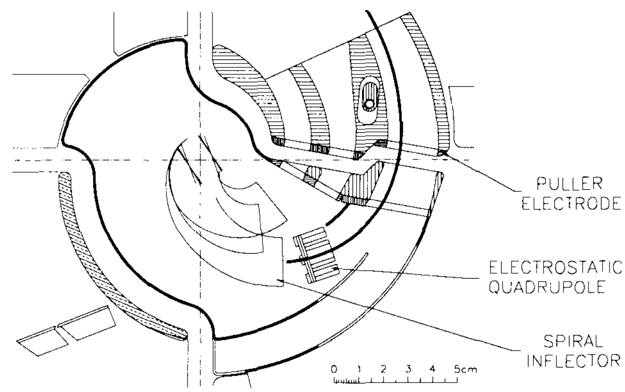

Figure 2: The position of the electrostatic quadrupole in relation to the spiral inflector and the puller electrode of SPC2.

3 Beam Development

3.1 Heavy ions

During the past three years a total of more than 30 different beams of carbon, oxygen, zinc, argon, krypton and xenon were delivered to experiments, ranging in energies from 85 MeV for $^{18}O^{4+}$ to 790 MeV for $^{129}Xe^{22+}$. We also tried to produce Li- and Na-beams with our ECR source. These beams could only be sustained for short periods, too short for injection into SPC2, and caused severe pollution of the source.

As it was believed that the transmission of heavy-ion beams through SPC2 could be improved by better focusing in the central region, a 15 mm long electrostatic quadrupole with a pole diameter of 12 mm was installed between the exit of the spiral inflector for the 9-turn orbit geometry and its first acceleration gap (figure 2). Insufficient space prohibits the installation of similar quadrupoles for the 16- and 32-turn geometries.

It is difficult to judge the overall effect of the quadrupole on the transmission. The 18.7% transmission for the $^{84}Kr^{15+}$ beam after installation of the quadrupole was indeed the best ever obtained for acceleration on the 6^{th} harmonic mode in SPC2. However, a 17.2% transmission had been measured for an $^{40}Ar^{8+}$ beam before the quadrupole was installed. On the 16-turn orbit (without quadrupole) a maximum transmission of 31.8% was achieved for $^{12}C^{5+}$. What can be concluded, however, is that the availability of the quadrupole in the central region makes the tuning of SPC2 much easier and quicker. Currently, a transmission of between 10% and 15% is considered to be acceptable for routine beam production runs in the 6^{th} harmonic mode, and of 20% or better for the 2^{nd} harmonic mode.

3.2 Polarized ions

Up to now, only polarized proton beams were delivered to experiments, ranging in energy from 66 MeV to 200 MeV. Typically, a polarization of 70% to 80% is now achieved, but initially we often had difficulties with depolarization effects. This was solved by making a detailed theoretical and experimental study of the causes for depolarization in the cyclotrons and beamlines [4]. Also the operational reliability of the ion source (commercially acquired) was unacceptable, and it was difficult to fine-tune the source for good beam characteristics. To alleviate these problems, we implemented the following modifications.

To increase the lifetime and voltage-holding capabilities of the dissociator, its capacitor was replaced with a vacuum capacitor and the cooling of the solenoid was improved. To measure the performance of the atomic beam formation section online whenever necessary, a pneumatically driven mechanism was designed and installed, which allows us to exchange the last rf-transition unit with the compression tube chamber used for such measurements, without venting this section. To facilitate better tuning of the source, a frequency counter was installed to monitor detuning due to temperature variations in the strong-field unit. Fixed procedures for setting the magnetic fields of the strong- and weak-field units were developed, and the Jacard [5] measurements can now be made with a spectrum analyser for improved sensitivity and ease of use.

The lifetime of the filament in the ioniser has been limited to a few days due to vibrations induced by a vacuum pump. It was increased – up to several months – by installing a damping device between the pump and the vacuum chamber. All the high-tension connectors and feedthroughs for the ioniser were replaced by either commercial or home-made ones with higher ratings. Almost every insulator and electrode in the ioniser was modified to increase its voltage-holding capability, and the cooling of the ioniser was improved.

We are even considering to replace our ioniser with an ECR-ioniser similar to the one used in the polarized ion-source for the PSI Philips Cyclotron, providing significantly improved operational reliability and a much lower energy spread in the beam. To avoid the reduction in polarization, which is often observed when using such an ECR-ioniser, we investigated magnet configurations resulting in narrower ECR regions (figure 3).

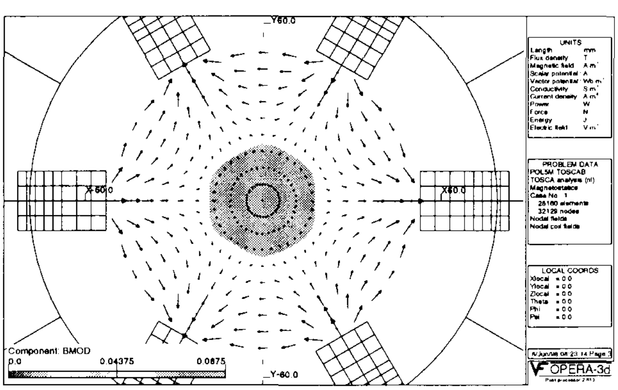

Figure 3: The ionisation region which has been computed for the magnet configuration of an ECR-ioniser designed for our polarized ion source, employing stronger and twice as thick permanent magnets for the hexapole field than those at PSI [6].

4 Beam-matching for Neutron Therapy

Our isocentric neutron therapy unit employs two dipole magnets for bending the beam through +70° and -160° respectively, and can be rotated about the axis of the incoming beamline by 360 degrees to aim at the patient in the isocentre from different directions. The beam-spill around the Be-target itself is monitored by the current measured on the four quadrants of a collimator. The total spill must be minimised by correct focusing. In addition, a segmented ionisation chamber down-stream of the target is used to monitor and maintain the flatness and symmetry of the neutron field, by ensuring that the ratios of opposing segments (top/bottom and left/right) are kept close to unity. At present this requires operator intervention to re-steer the beam when the gantry is rotated to a different angle. The main reason for this is that the beam is neither perfectly aligned nor totally achromatic at the entrance to the isocentric system.

Beam matching with dipoles and quadrupoles still has to be done separately for each treatment angle to reduce the total beam-spill. It has been found that this is more difficult for angles on one side of the upright position of the gantry than on the other, and that it is expedient to add a cross-over of the off-momentum rays, when the gantry is on the former side, to make the beam transport as non-dispersive as possible. New control software has been tested during a recent shut-down, which provides feedback from the quadrants and the ionisation chambers to the power supplies of all magnets involved. In future, the beam will first be set up manually for each treatment angle required on a particular day, and these settings will then be selected automatically whenever that angle is needed, including the quadrupole settings for the cross-over. During treatment, a feedback system will correct and maintain the neutron-flux ratios measured on the segmented ionisation chamber.

5 Dispersion-matching for the K600 Spectrometer

This QDD magnet spectrometer has been in use for some time now as a high-resolution device by adjusting the properties of the incident beam to provide dispersion-matching at its target [7]. The beam transport system from the SSC to the spectrometer incorporates a double-monochromator, providing a dispersion at the exit of the monochromator, which is known theoretically. A system of six quadrupole lenses is then used in the next section of the beamline to achieve dispersion and emittance matching to the spectrometer.

In practice, a computer program converts the known kinematic factor K, the dispersion coefficient C and the target transmission T to empirical settings for the quadrupoles to provide a reasonable focus on target and approximate matching. The experimentalist then iteratively varies the last two quadrupole settings to optimise the observed resolution of the detected particle spectrum. If this is not successful, the six quadrupoles are re-set for a new dispersion coefficient, and the optimisation process is repeated. Usually only three iterations are required to obtain acceptable results.

Beam dispersion-matching can now be done routinely, and a resolution of 26 keV has been achieved for 200 MeV protons scattered elastically off a 0.5 mg/cm^2 gold target. This is about twice as good as the best resolution obtained with an achromatic beam tune. Perhaps more important, however, is that the use of the dispersed beam with a dispersion-matched spectrometer avoids the need for very narrow energy-selection slits in the beamlines. This reduces the time needed to develop a high-quality beam and minimises beam halo. With a sufficient count rate, optimising the incident beam to the tuned spectrometer typically takes only 20 to 30 minutes.

6 Control System

The distributed control system of the NAC cyclotrons [8] is performing well with significantly improved reliability and speed. The communication component of this system was modified and upgraded to 32-bit code, contributing to the improvement. Regarding the operator interface, the "mouse" has now become the standard means of interacting with operator consoles, but page selection is still done via a reduced-function keyboard as this has proved to be the fastest method. The software developed for the original electronics of beam-profile measuring equipment was recently expanded to incorporate control of different hardware used for the beamlines of SPC2 and new experimental areas. It is now possible to access the information from any beam-profile device and display it on any console of the main control system.

For the reasons explained already in section 4, the control of the beamline magnets in the neutron therapy gantry has been incorporated into the main control system, and the process of setting the magnets for each utilised angle is being automated. Closed-loop control will be provided to adjust parameters dynamically during treatment. Control of the RF systems is also now being integrated into the main control system. Obsolete hardware is being replaced, and more flexibility and intelligence will be incorporated. A full graphics interface is being developed which will display significantly more status information than at present. Start sequences will be automated as far as possible so that the cyclotron operators can perform the re-tuning of the amplifiers during energy changes without assistance from RF personnel.

7 Future Perspectives

Although beam utilisation at NAC is already very high, it can be improved even further, in particular with respect to the 200 MeV proton beam for radiotherapy. For this purpose, and to make proper use of the high beam quality from the SSC, we have embarked on the development of a second proton therapy station with innovative design characteristics and spot scanning [9]. This requires a much more stable beam than that which can be provided at present. To achieve it, we plan to use phase measurements with feed-back to the main power supply of the sector magnets. The performance of the existing phase measurement system was improved significantly in recent years, but at present the lowest beam intensity that can be monitored reliably is still of the order of 50 to 100 nA, while we need a sensitivity of a few nA. Such a system is currently being developed in collaboration with the Forschungszentrum Jülich in Germany. We have also proposed a dedicated flat-topping system for the SSC [10], to provide higher beam currents for isotope production.

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