# OPERATION AND DEVELOPMENT OF THE NAC ACCELERATOR FACILITIES

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## ABSTRACT

The NAC accelerator facilities have been in operation since the beginning of 1987. Proton beams have been used for isotope production, nuclear physics, neutron therapy and radiobiological experiments. The existing accelerator facilities at the NAC, their performance and various improvements are described.

## 1. INTRODUCTION AND DESCRIPTION OF FACILITIES

The k=200 MeV cyclotron and other facilities at the NAC[1)] have been constructed for the production of radioactive isotopes, for radiotherapy and for radiobiological and nuclear physics experiments. Proton beams in the energy range 27 to 200 MeV as well as alpha particle beams have been in use at the NAC for more than two years. At present the NAC facilities consist of an 8 MeV injector cyclotron, a 200 MeV separated–sector cyclotron, radioisotope production facilities, a 66 MeV (proton) isocentric system for neutron therapy, a 1.5 m scattering chamber, a 7 m neutron time–of–flight facility, a 24 cm diameter by 36 cm long NaI(Tl) gamma detector with a six–sector anti–coincidence plastic shield and a three–arm gamma correlation table for nuclear physics experiments. Results of the first two years of operation are discussed in terms of operational statistics, beam characteristics and accelerator performance and development.

## 2. OPERATING SCHEDULE AND STATISTICS

The cyclotron is operated according to a fixed schedule. On Monday mornings a 66 MeV proton beam is prepared. This beam is used for isotope production on Monday and Wednesday nights and on Tuesdays, Wednesdays and Thursdays for therapy. On Thursday nights a light–ion beam is prepared for nuclear physics experiments. From Friday through to 08h00 on Monday the beam is used for nuclear physics experiments. During therapy sessions the beam can be increased to 60 $\mu$A and switched over to isotope production in less than 15 seconds, while a patient is being positioned. The time required for an energy change varies with the beam energy and intensity requirements. Preparation of the 66 MeV beam at an intensity of 80 $\mu$A takes approximately 5 hours whereas a beam in the 150 to 200 MeV energy range requires up to 20 hours for a new energy, including time needed for minimizing the halo for nuclear physics experiments.

Table 1 shows the distribution of scheduled time for 1987 and 1988. During the first year of operation beam was on target or available for an average of 38 shifts per month. The figure for the second year is 47 shifts. The beam time loss due to retuning of the beam after power dips, especially late in the summer months, necessitated the acquisition of an uninterruptable power supply with a capacity of 3.2 MVA. This power supply can keep the facility going for ten minutes in event of a power failure.

Table 1: Distribution of scheduled time

| Year | 1987 | 1988 |
|---|---|---|
| Scheduled time<br>(normalized to 100%) | 6157 hours<br>100% | 6840 hours<br>100% |
| Interruptions | 14.1% | 6.4% |
| Retuning of the beam after power failures | 4.6% | 3.8% |
| Beam development | 2.0% | 4.0% |
| Energy change and beam tuning | 18.8% | 19.9% |
| Beam time | 60.5% | 65.9% |
| Scheduled time as % of calendar time | 70.3% | 77.9% |

The unscheduled time for 1988 (22.1% of calendar time) was divided between maintenance and development (18.6%) and holidays (3.4%). The main sources of interruptions have been the electrostatic channel of the injector cyclotron, the buncher in the beamline between the two cyclotrons, the power supplies and cooling water of the separated–sector cyclotron. Improved design and construction have essentially eliminated these problems.

## 3. THE LIGHT–ION INJECTOR CYCLOTRON

The light–ion injector cyclotron (SPC1) is a k = 8 MeV solid–pole cyclotron. Proton beams in the energy range 1 to 8 MeV have been accelerated and extracted. External proton beam intensities of up to 320 $\mu$A at 3.14 MeV (the energy which corresponds to 66 MeV in the main machine) have been achieved. The emittance of a 100 $\mu$A proton beam at this energy is $5\pi$ mm mrad and $12\pi$ mm mrad in the vertical and horizontal directions respectively. A second axial slit has been installed for pulse–length definition. With the aid of this slit the extraction efficiencies of both SPC1 and the separated–sector cyclotron (SSC) have been improved.

## 4. OPERATION OF THE TRANSFER BEAMLINE

The transfer beamline transports the beam from the injector cyclotron to the SSC. The first stage in optimising this line is to use magnet settings from an earlier run at the same nominal energy. This process is automatically performed by the control computer system, using stored parameters. The emittance of the beam is then measured immediately after extraction from the injector, using the method of three distances, utilizing 3 profile monitors. These emittances (horizontal and vertical) are used to determine the eigen–ellipse parameters required for the theoretical equilibrium orbit at injection radius in the SSC. The measured emittances are also used in the TRANSPORT program[2)] to calculate the quadrupole magnet settings required to match the beam to the eigen–ellipse in the SSC.

Fig. 1 shows the calculated beam envelopes obtained from this process, adjusted very slightly (i.e. Q8 by 2% and Q14 by 4%) to agree with the beam widths observed on the profile monitors located at various places along the line. The horizontal (x) and vertical (y) half–widths are indicated separately, and show good agreement with the plotted beam envelopes.

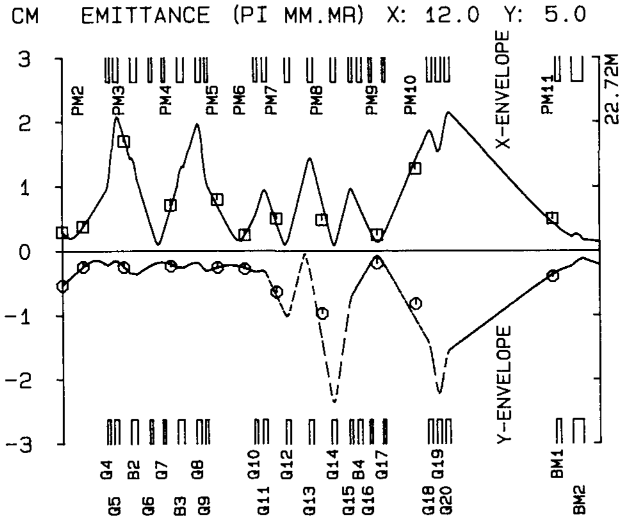

Figure 1: Calculated beam envelopes for the transfer line. The measured beam widths are also shown.

The final matching to the SSC in the x–x' and y–y' planes respectively is achieved independently by using orthogonal quadrupoles (see fig. 1). By utilizing the extraction harps in the SSC, the matching in x–x' space can be optimized directly by adjusting Q13 until a well–matched beam is observed, i.e. with constant beam width. For the vertical direction no profile monitor is currently available before extraction to indicate the beam height directly. In practice, the matching in y–y' space is optimized by adjusting quadrupole Q14 until no losses are observed on the axial collimators in the SSC (these are located above and below the beam path from injection to extraction radii, in one of the valley vacuum chambers).

Because of the transfer beamline geometry, the energy–spread introduced by the buncher is quite well matched radially within the SSC, without using the additional quadrupoles provided. Similarly, there is no need to make a special effort to match the energy–dispersion arising from the energy–spread of the injector.

As more beam energies are selected and used, it becomes possible to scale the beamline element settings from the nearest previously–used energy: in most cases we find these values adequate for operating the transfer beamline, without much adjustment.

## 5. THE SEPARATED–SECTOR CYCLOTRON

From the start it was clear that the separated–sector cyclotron is a reliable machine and easy to operate. An important reason for this is the fact that the rf system works reliably at dee voltages of up to 250 kV. At this voltage a spark in one of the resonators occurs about once in three days. Switch–on afterwards takes place automatically within 10 seconds. The vacuum system also operates reliably in the $10^{-7}$ mbar range. One turbo–pump has been damaged since start–up of the machine in 1985. Initially some of the magnet power supplies oscillated at the higher currents. This problem has since been rectified.

Figure 2 shows the last few orbits before extraction for 200 MeV protons. The inherent orbit separation is 7 mm but with a centering error approximately equal to the orbit separation, a separation of 14 mm can be obtained over an appreciable number of orbits because $\nu_x$ is close to 1.5.

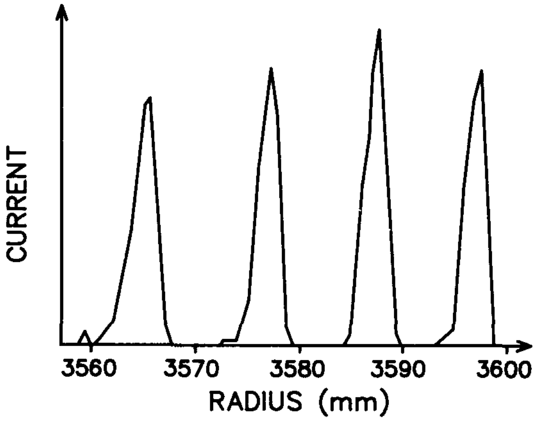

Figure 2: Orbits near extraction in the SSC for 200 MeV protons.

In order to maintain this condition, the magnetic field, the dee voltage and phase as well as the phase of the beam from the injector must be stable with time, especially when the SSC field has not been isochronized properly. The stability of the magnetic field has been improved appreciably by stabilizing the average temperature of the inlet and outlet cooling water, instead of the inlet temperature. An extraction efficiency of 90% has been achieved for 200 MeV protons, using two septum magnets for extraction. An electrostatic channel is available for extraction from the SSC but has seldom been used because of the good results that could be obtained without it, and because it is not as robust as the magnetic channels. Table 2 shows the percentage transmission through the SSC using only the septum magnets as extraction components for 66 MeV protons. All losses occur on the collimator of the first septum magnet.

Table 2: Transmission through the SSC, for 66 MeV protons

| Beam Current (μA) | Transmission (%) |
|---|---|
| 100 | 99.6 |
| 120 | 99.1 |
| 140 | 98.2 |
| 157 | 97.1 |
| 196 | 95.6 |

At currents above 100 μA, beam losses increase sharply. This is partly due to the septum thickness (7 mm) of the first magnetic channel but it is also due to the increase in the beam width at extraction because of the energy spread imparted to the beam by the buncher in the transfer line and the consequence of this in terms of the beam width at injection and extraction in the SSC. A slit which can control the beam width (and thus the energy spread) on the first few orbits is planned for the SSC. The horizontal and vertical beam emittances for a 30 μA, 66 MeV proton beam are $5\pi$ mm mrad and $2.5\pi$ mm mrad respectively.

For neutron time–of–flight measurements the time interval between beam pulses is increased by a factor varying from 5 to 7, using a pulse selector, installed in the SSC. The injected beam passes on its way to the center of the machine through the gap between the two horizontal plates of the pulse selector which carries a dc voltage on which an ac voltage is superimposed at a frequency equal to a fraction of the cyclotron rf. Those beam pulses that are deflected vertically are stopped on an adjustable slit in the centre of the machine.

From the start two beam diagnostic harps have been used to measure orbit patterns near extraction in the SSC. These harps are 50 mm long and can be moved radially over a useful distance of 250 mm. Because of the convenience of observing several orbits while the beam is tuned, the idea was extended to the central region by the installation of a 400 mm long harp on which the first 8 orbits can be observed. The harp moves vertically into position when required. It has been very useful for orbit centering and emittance matching.

There was also a need for a quick way of observing the orbit pattern at extraction at high beam intensities (approximately 100 μA). A scanner which can be moved through the beam radially has been installed. The last three orbits, again at 66 MeV, can be seen. It takes two tenths of a second to acquire the 240 current measurements before the orbit pattern is displayed.

For a new beam energy the main coil and trim–coil currents are calculated from measured field data and are set to these values by the control computer. Phase measurements are carried out with a movable phase probe in the SSC. New trim–coil and main coil currents are calculated from these phase measurements and are again set by the control computer. For a new energy in the 120 MeV to 200 MeV range this process can be repeated five times over a period of two hours to achieve maximum phase deviation of not more than $5^0$. The rf phase is fine–tuned for minimum energy spread while the beam is observed on one of the harps near the extraction radius. The beam is centered by tuning the central region magnets while the beam is observed on the long harp in the central region and the two movable harps near extraction. A computer program has been developed for beam centering, using the orbit pattern measured with a differential probe. The injection process has also been simulated on a computer. Operators can vary the different magnet currents and observe the computed beam behaviour on a screen.

## 6. HIGH–ENERGY BEAMLINE

### 6.1 Operation of the Extraction Beamlines

Figure 3 shows the layout of the beam lines and cyclotrons at the NAC. For tuning the beamlines after extraction, the horizontal and vertical emittances are measured using the three–distance method. The resulting values are used in TRANSPORT to determine the settings for the beamline elements. The agreement between the measured and calculated values is also very good. The measured emittance in the x–x' plane ($15–20\pi$ mm mrad) for a beam current of 50–80 μA is larger than that originally assumed when the beamlines were designed ($8\pi$ mm mrad).

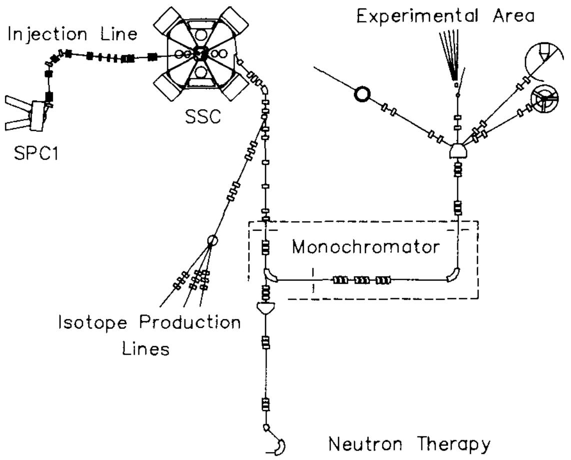

Figure 3: Existing beamline layout of the facility

The reason for this increase is the longer bunch length from the injector which must be accepted in order to obtain the required beam intensity. A larger bunch length corresponds to a greater energy–spread from the injector, and the buncher also contributes to broadening of the beam inside the SSC, and hence to an increased radial emittance.

### 6.2 Beamlines to Isotope Production Area

Because of the increased radial emittance, and a change in the specification for beam spot size on target for isotope production, the beamline leading to the isotope vault was redesigned. Just prior to entering the vault the beamline divides into three branches, with a switching magnet at the vertex.

This magnet was moved back from the targets and a triplet of quadrupoles with 150 mm apertures was installed on each of these branches. At the same time the existing quadrupoles leading up to the switcher were rearranged to form a 2–triplet telescope. The acceptance of this line is now more than $50\pi$ mm mrad, and it is able to focus intense beams of protons to smaller than 20 mm spot sizes on target.

The layout in fig. 3 shows the new beamline to the isotope production area, after the rearrangement in October 1988. Beams have routinely been delivered to the isotope production vault, without any difficulty.

### 6.3 Beamlines to Experimental Areas

In the beamline leading to the experimental vaults there is an orthogonal quadrupole system with which the horizontal and vertical beam size can be adjusted independently. The system works well for beams with emittances of $\lesssim 11\pi$ mm mrad. However, for larger emittances, the settings are rather critical, because it is easy to lose part of the beam owing to over–focusing or steering errors. For these larger emittances a 2–triplet telescope would in fact be preferable. A double monochromator of the type proposed by Hinterberger$^{3)}$ follows this section, containing two large 2 m radius 90° dipole magnets, and a system of quadrupole magnets which permits a variety of conditions to be met at each target location. This system performs well in practice. Many of the experiments which use this system are very sensitive to the beam halo, which is easily suppressed by using the slits in this system. A double set of slits at the entrance to the monochromator enables the beam size and divergence to be limited; a set of slits after the first 90° dipole provides for energy–selection, while the slits before and after the second 90° dipole can be used as "clean–up" slits. For a 200 MeV proton beam, where the halo is a major problem, 0.006% of the beam lies outside a 25 mm diameter circle and 0.06% outside a 3 mm diameter circle at the target position.

## 7. BEAMLINE DIAGNOSTICS

There are two positions in the transfer beamline from the injector, and two in the beamlines beyond the SSC, where the emittances can be measured using the three–distance method. The measured values seem to be reliable, and provide a basis for calculating realistic values for the settings of the beamline elements.

The phase probes in the beamlines can now be used in two different modes, i.e. to measure the phase of the beam, and also as non–destructive current measurement devices. In the latter mode, the current derived from the phase probe is calibrated against a nearby Faraday–cup reading. The accuracy of these measurements is better than 1%. This development allows us to monitor current accurately even at high values where problems are experienced with overheating of Faraday cups.

There are at present 4 positions along the various beamlines where the direction of the beam can be corrected by means of a semi–automatic process, using information from profile monitors (harps and scanners). After some initial difficulties, requiring improvement in the rise–time of the scanner electronics, and the relocation of a number of scanners, the system now operates satisfactorily.

## 8. FUTURE FACILITIES

The facilities presently under construction at the NAC are listed in table 3 with their respective expected completion dates. The spectrometer and beam swinger have the highest priority. The k = 11 MeV heavy–ion injector cyclotron will be almost identical to the existing light–ion injector.

Table 3: Future Facilities

| Facilities | Expected completion dates | |
|---|---|---|
| k=600 spectrometer | June | 1990 |
| Beam swinger and 200 m time–of–flight facility | October | 1989 |
| Heavy–ion injector cyclotron | | 1991 |
| ECR ion source | June | 1989 |
| Polarized–ion source | Early | 1990 |

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