IMPACT OF THE CYCLOTRON RF BOOSTER ON THE 500 MeV PROTON BEAM PRODUCTION*

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Abstract

The TRIUMF cyclotron routinely accelerates ~220 µA of H^- ions, extracting protons simultaneously to four external beam lines. The radioactive beam facility ISAC, now operating at 10-20 µA ~500 MeV protons, will soon require up to 100 µA at 500 MeV. The CHAOS experiment on the π^+, π^- secondary beam line also requires a high intensity beam (~140 µA, 500 MeV) but with a short (2 ns) bunch length. High current operation with 2 ns beam has been facilitated by the 4th harmonic auxiliary acceleration cavity [4]. The 2 ns beam structure is now achieved by phase compression as the energy gain per turn increases near extraction. The paper focuses on improvements in the reliability of this cavity and its rf coupler. The higher energy gain per turn also reduces H^- stripping losses (by about 33%) in the high energy region, hence increases the allowed beam intensity for a given beam activation. The total current will soon be increased to about 300 µA to allow for ISAC requirements.

1 INTRODUCTION

In December 1999 TRIUMF celebrated 25 years of cyclotron beam operation. The intrinsic flexibility of the machine, made possible by the acceleration of H^- and the ease of extraction by stripping, has been increasingly exploited over the years. During 1998 a fourth extraction system and beam line (BL2A) were installed to direct a fraction of the high intensity beam to the ISAC radioactive beam facility [1]. By the end of 1999 this system was tested to the design goal of 100 µA 500 MeV protons using a prototype Molybdenum target [2].

The vault layout of the four extraction systems which can operate simultaneously is shown in Fig. 1. Routinely up to 150 µA are extracted at 500 MeV down BL1A, up to 20 µA at ~495 MeV down BL2A, and 50 µA between 70 and 100 MeV down BL2C for isotope production. Low current beams between a few nA and a few µA can be extracted down BL4. This corresponds to a total internal accelerated beam availability of ~220 µA. Within the next two or three years ISAC will routinely be operating up to the design current of 100 µA with an increased demand on the total available cyclotron beam current of up to ~300 µA, of which 250 µA (instead of the present ~170 µA) will be required at high energy. This would lead to an undesirable increase of machine activation by 40 to 50% due to the corresponding higher beam loss. However, using the auxiliary accelerating cavity, AAC, or "rf booster cavity", which was originally proposed by J.R. Richardson in 1983 [3] and designed, prototyped, and installed in 1989-1990 [4], electromagnetic and gas stripping losses can be reduced by increasing the rf accelerating voltage per turn and therefore reducing the number of turns in the 400-500 MeV region. Although the rf booster was tested during beam development and showed close agreement with beam dynamics predictions and simulations [5,6], it never achieved, until recently, a level of reliability suitable for routine beam production.

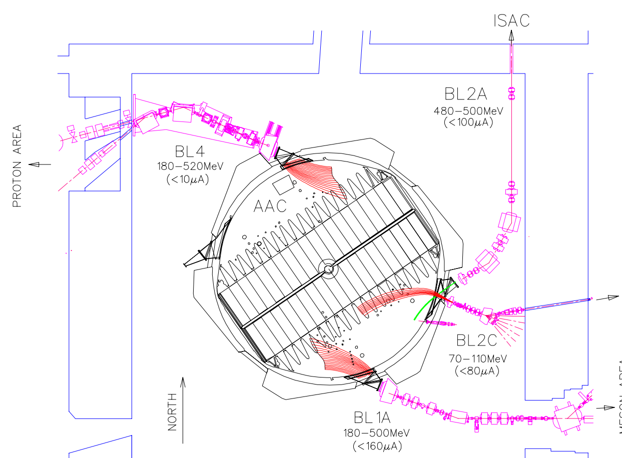

Figure 1: Layout of cyclotron vault and of four systems for simultaneous extraction.

The need for reliable operation of this cavity became even more compelling in light of the additional requirement from a BL1A π^+ π^- user to reduce the time structure of the high energy beam from ~4 ns to ~2 ns. Previously this had been achieved through defining slits in the cyclotron centre region, but not without a substantial reduction (20 to 30%) of the total accelerated beam intensity. The increase in accelerating voltage obtained with this cavity causes sufficient compression of the beam phase interval so that slits are no longer required. The intensity is not reduced, in fact it increases slightly due to

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a reduction in stripping at high energy. The price is a fractional increase in energy spread and emittance of the extracted beams, roughly proportional to the fractional increase in radial gain per turn at extraction. Since the beam line acceptances both for BL1A and BL2A are much larger than the emittances of the extracted beams, this is of no consequence for meson production down BL1A or production of exotic ions at the ISAC target.

Beam production for the period 1995-2000, in terms of yearly hours of actual cyclotron beam operation and yearly mAh of total cyclotron proton beam charge delivered, is shown in Fig. 2. The cyclotron availability over the same period, in terms of hours of cyclotron operation per year versus hours scheduled, and BL1A beam intensity delivered per year versus intensity scheduled, is shown in Fig. 3. During 1999 we had a substantial interruption in high intensity beam delivery because of a sudden failure of a cooling vessel at the BL1A beam dump. At the same time during 1998 and 1999 we limited the accelerated beam current because of operation with defining slits. Using the AAC as a reliable operational unit was very helpful in achieving 93% availability, in terms of both hours and intensity during year 2000.

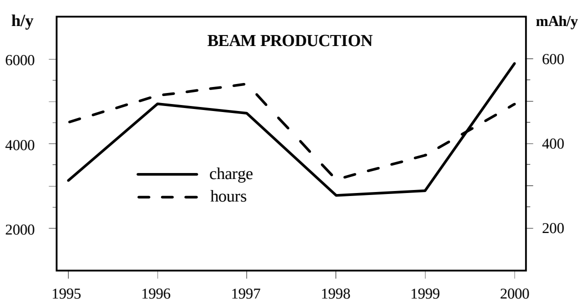

Figure 2: Hours per year of beam operation and charge per year delivered during 1995-2000.

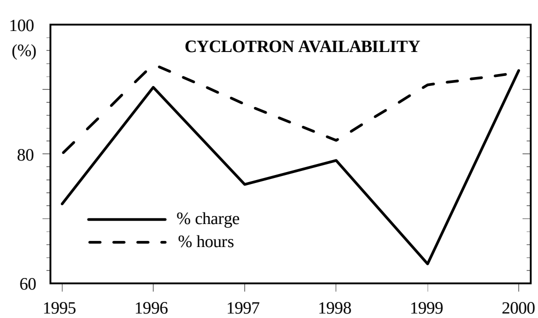

Figure 3: Beam availability in terms of hours per year and beam charge per year (% of delivered vs scheduled).

2 THE AUXILIARY ACCELERATION CAVITY

2.1 Concept

The 4th harmonic auxiliary acceleration cavity or rf booster has been described elsewhere [7]. In the accelerating mode the cavity operates at 92.2 MHz, in phase with the fundamental rf. It consists of two trapezoidal structures facing each other symmetrically above and below the median plane with dimensions $\lambda/4$ radially and $\beta\ \lambda/2$ azimuthally [Fig. 4]. The orbiting ion receives two acceleration impulses at each passage through the lateral electric fields. For the design voltage of 150 kV, the energy gain per passage rises sinusoidally from zero to ~300 keV in the radial interval between the 370 and 520 MeV orbits.

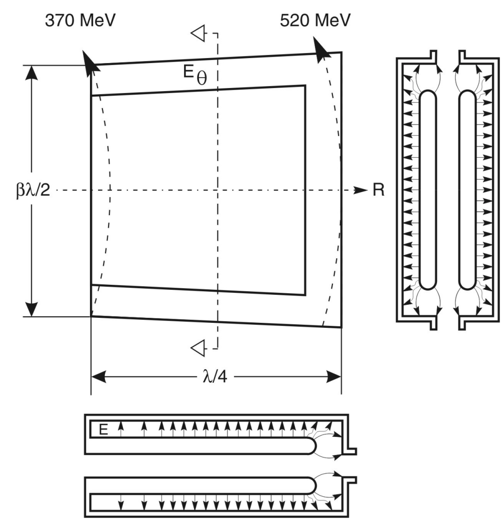

Figure 4: Schematic view of the AAC.

Simulations and measurements confirmed [5] that at the above voltage and for a typical cyclotron vacuum of 5.10^{-8} Torr a reduction in overall tank activation in excess of 33% is obtained. This reduction is significant due to the fact 1) that the AAC radial location overlaps with the high energy region where most electromagnetic stripping loss occurs (~8%) and; 2) that gas stripping losses have higher weight on tank activation at higher energy. Alternatively, using the AAC, one can increase the high energy beam intensity by about 50% without significantly increasing the level of tank activation. Since tank activation is a rather firm limitation, this will permit the high energy beam current to be raised to a total of 250 µA , in accordance with planned ISAC requirements the overall cyclotron beam current being 300 µA.

2.2 Phase Compression

The theory of beam phase compression/expansion in cyclotrons was introduced in 1970 by Muller and Mart [8] and developed by W. Joho in 1974 [9]. Briefly, a radial gradient in the accelerating field from an rf cavity gives rise to a magnetic time-varying field 90° out of phase with the accelerating field. Positive radial gradients focus or compress off-phase particles longitudinally, while negative gradients defocus or expand the bunch length. Assuming the cyclotron to be perfectly isochronous over a certain radial extent, and the phase difference between fundamental and mth harmonic cavity to be zero or $2\pi m$, one can evaluate the phase ϕ_f at radius R_f from the initial phase ϕ_0 at radius R_0 by solving

$$E_{G1}(R_0)\sin(\phi_0) = E_{G1}(R_f)\sin(\phi_f) + (E_{Gm}(R_f)/m)\sin(m\phi_f)$$

Here E_{G1} and E_{Gm} correspond to the peak energy gain per turn for fundamental and mth harmonic acceleration respectively. In our case m=4, E_{G1} is typically 0.32 MeV and $E_{Gm}(R_f)$ is ~0.3 MeV at the final extraction radius.

A typical phase compression of the accelerated bunch produced by the AAC, powered at 140 kV, was measured and is shown in Fig. 5. The extracted phase interval was reduced from 32° (or 3.85 ns) to 18° (or 2.16 ns), in agreement with calculated values [4].

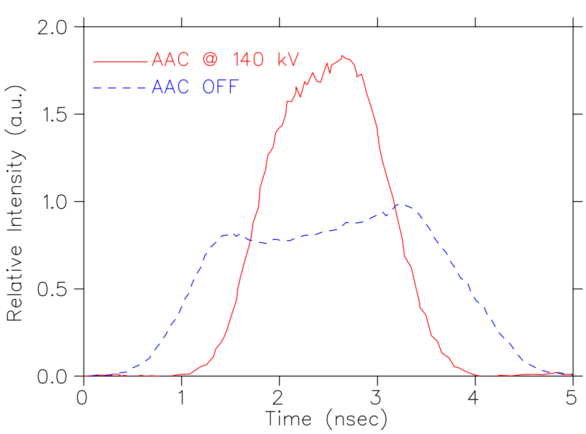

Figure 5: Time structure of the extracted beam with AAC off and AAC powered at 140 kV (1ns = 8.3°).

2.3 Mechanical Structure

The lower and upper halves of the AAC resonating structure are inside the cyclotron vacuum attached independently to the floor and lid chamber and are separated by a 64 mm distance to allow space for the beam and its vertical misalignments, and so avoid activation. A cross section of the lower half is shown in Fig. 6. The cantilevered strong back (with a stiffness of 220 N/mm at a frequency of 20 Hz) supports the beam side panel and the hot arm. This is connected to the ground arm through the root. All rf surfaces are made from 1.6 mm thick OFHC water cooled copper sheets. The two half structures are designed to be installed and removed remotely. The coupling loop feedthrough is connected to the lower structure and is designed with a smooth 50 Ω transition to a 6 in transmission line. A 11 cm diameter alumina window is used. Coarse tuning is obtained by shimming the ground arm and hot arm at installation, whereas fine-tuning is provided by water cooled hinged flaps, built into each ground arm. The existing power amplifier can deliver 150 kW of power that will be required for the 250 μA beam.

2.4 RF Commissioning

A view of the lower half of the AAC installed in the cyclotron tank is shown in Fig. 7. One can see the lower beam side panel surrounded by the electrode tips of the cavity hot arm situated above the ground arm panel which has its edges turned up to form flux guides for maintaining minimum rf leakage. The vacuum tank region behind the main cyclotron resonators, in which the AAC is located (Fig. 1), would be rf field free if we had perfect symmetry and there were no breaks in the rf magnetic flux guides. However, perfect symmetry does not exist in practice and the rf magnetic flux guides have to be interrupted to allow the beam to get through. The result is an rf leakage field in the beam volume from the AAC accelerating cavity in addition to the rf leakage from the fundamental rf resonators [10]. The 4th harmonic leakage, being caused by a rather shorter λ/4 (about 75cm), is more

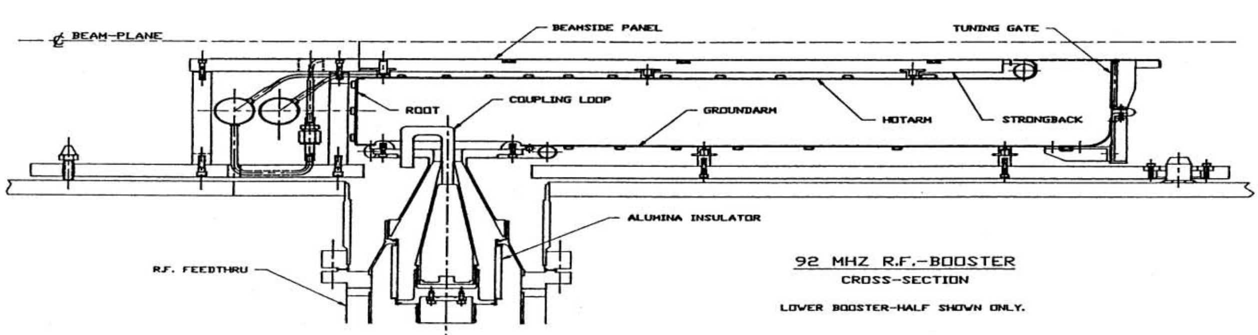

Figure 6: Cross section of the lower half of the AAC.

dangerous and difficult to control. It can induce parasitic modes around elements or small volumes with a size comparable to λ/4. During our first tests several diagnostic elements were damaged or failed. Telescopic shorting contacts, which connect the upper and lower ground arms, were added to the cavity in four locations between ground arms outside the 520 MeV beam orbit to help reduce the rf leakage. As a result of an rf leakage development program, these telescopic shorting contacts were replaced by continuous shorting contacts. These caused a substantial reduction of the rf leakage field, compatible with routine operation.

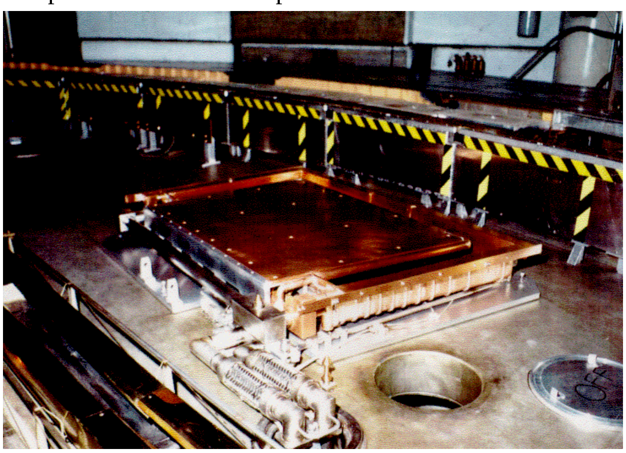

Figure 7: View of the lower AAC structure.

From 1990 to 1998 there were several failures of the rf feedthrough. Upon close examination of the feedthroughs there was indication of electron tracking. This lead to the measurement of the local magnetic field. Its direction coincided with the direction of electron tracking. SUPERFISH simulations also indicated that electric field gradients were highest at the ceramic to metal joint where the failures were occurring. Fig. 8 shows the rf window with and without shields added around the metal to ceramic joints to reduce the electric field. The new design with shields was installed and tested in March 1999 with very little multipacting effects as compared to previous conditioning periods. Since March 2000 the feedthrough has been routinely used for a very productive beam delivery period with no rf problems.

Although a variable line stretcher was installed in the 60m long transmission line to insure a proper length for operating into a true parallel resonant circuit, the amplifier still showed signs of instabilities. Neutralization is usually not required in a grounded grid amplifier, but in this case where the amplifier is connected to a high Q resonant load via a long transmission line, neutralization was added to reduce the high impedance side-band frequencies [11]. These impedances were further reduced by anode damping.

Figure 8: The AAC feedthrough window with and without copper shields covering the metal to ceramic joints.

The 92.2 MHZ is generated from an analogue phase locked loop, which automatically locks on to the 23.06 MHZ cyclotron dee voltage. In the case where the dee voltage is not available, for example during and after a spark, a ;digital sample-and-hold circuit inside the phase locked loop prevents the frequency from drifting. Two independent PID control loops are used for amplitude and phase regulation. Voltage fluctuation is less than 0.1% and phase fluctuation is less than 1°. The control and optimisation procedure of the rf booster by the operators is very smooth. The amplitude is set by the rf group at its maximum reliable value (above 120 kV). The phase is then optimised by the operators by maximizing transmission to 500 MeV, and minimizing the time-of-flight through the machine, say from about ~340 µs with booster off to ~310 µs with booster on. Once optimised, and if the fundamental rf is stable, the booster phase will not need to be readjusted for several days.

3 OPERATING EXPERIENCE

The 4th harmonic AAC, which was originally intended for and tested during the KAON project definition study, has now become a reliable key element for cyclotron operation. The AAC converts the 4 ns high intensity beam bunches from the centre region to the 2ns time structure requested by the BL1A users.

The positive effect of the reduced beam time structure on the time resolution of the secondary particles for the CHAOS experiment is clearly shown in Fig. 9. With booster on the π^+, μ^+ and e^+ are well separated and the desired 2 ns structure is achieved (Ref. 12).

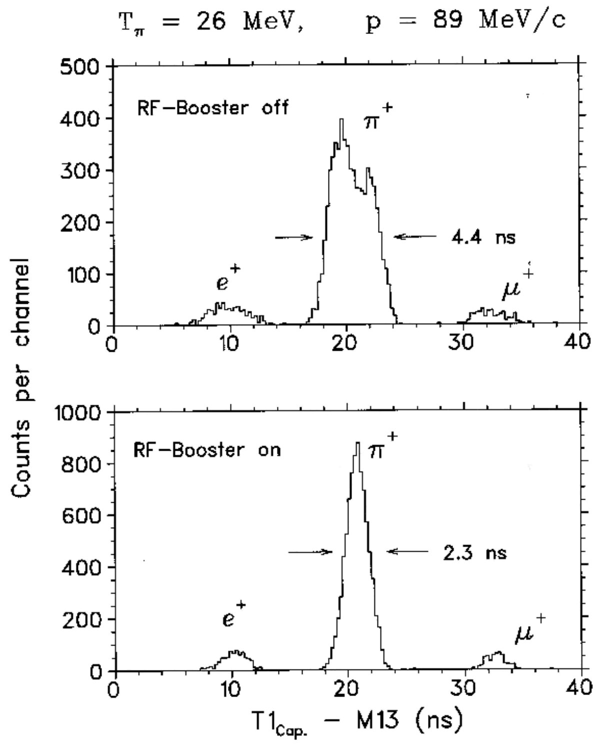

Figure 9: The e^+ π^+ μ^+ time distribution at the CHAOS detector with and without rf booster.

The effect of the AAC on the total average current actually delivered during three typical 10-week high intensity periods in 1996, 1998, and 2000 is shown in Fig. 10. From an average current above 180 μA in 1996 (before introducing the more stringent time resolution requirement), we suffered a reduction of the average current to less than 160 μA during the 1998 period due to the use of slits to provide the 2 ns time structure. During a similar period in 2000, and using the AAC, we were able to raise the current to 195 μA. The effect in terms of intensity will be more dramatic during the planned operation at 300 μA.

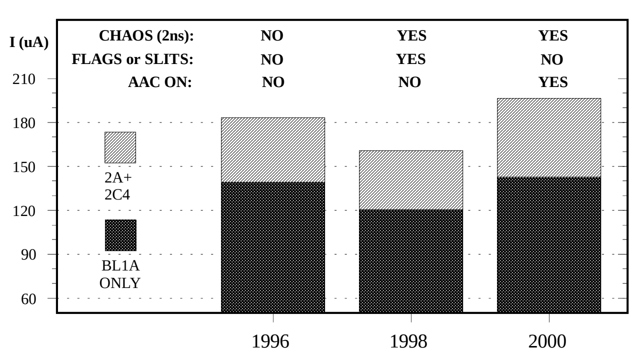

Figure 10: Average current during typical high intensity 10-week periods (1996, 1998, 2000), with different time structure requirements

We believe that the major remaining limitation to achieving 300 μA is caused by beam related electrode overheating in the centre region. The precise location of overheating has not yet been determined. Once this is done additional cooling may solve the problem. A pulsed beam with 400 μA peak current, 200 μA average, was previously accelerated to 500 MeV (Ref. 13). This would tend to exclude the limit to the increase in current to be space charge or beam dynamics related. A brighter H^- ion source is also being developed.

4 ACKNOWLEDGEMENTS

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