THE TRIUMF FACILITY AND CYCLOTRON DEVELOPMENTS*

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Abstract

The TRIUMF cyclotron has delivered, over the past several years, simultaneous proton beams to meson users, proton users, and low energy proton users with total intensity around 200 μA at energies between 60 and 500 MeV. Since 1998 it has also been delivering routinely 500 MeV protons to ISAC with proton currents up to 40 μA on target. Initial ISAC experiments were performed with singly charged radioactive ions at target/ion-source energies (E ≤ 60 keV). A cw linac consisting of a 35.4 MHz 8 m long RFQ and a 106 MHz DTL accelerator structure has recently been commissioned to energies between 0.153 and 1.53 MeV/u for ions with A<30. A superconducting accelerator to extend the energy range to 6.5 MeV/u (or higher) has been funded. A charge state booster will extend the mass range from A ≤ 30 to A ≤ 150. In order to increase the primary proton beam current for ISAC to 100 μA as planned, and keep up with other user demands, the cyclotron current will be increased to 300 μA within one or two years. Preferably this should be achieved without increasing the activation of the cyclotron tank caused by beam stripping losses, mainly at high energy. Challenging requirements are originating from the T1 meson users, demanding a reduction of the beam pulse duration from 4 ns to 2 ns. A 92 MHz 4th harmonic rf booster cavity located in the high energy acceleration region of the cyclotron has been demonstrated to satisfy both above requirements.

A cyclotron refurbishing program, was also initiated to keep reliability at the present 90% level or better.

1 STATUS OF THE TRIUMF FACILITY

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 cyclotron high intensity beam to ISAC. By the end of 1999 the new extraction was tested at the design goal of 100 μA 500 MeV protons, on a prototype Molybdenum ISAC production target [1].

The layout of the basic facility is given in Fig. 1. The 500 MeV H^- cyclotron is at the centre. Toward the East during high intensity operation, 150 μA, 500 MeV protons are routinely delivered to the meson production targets T1 and T2. A 50 μA proton beam between 60 and 120 MeV is extracted down BL2C for isotope production. Periodically this beam is reduced to nA or sub nA currents for proton irradiation of materials or for proton therapy (eye melanoma). Toward the West, BL4A accommodates low intensity, variable energy users (I < 10 μA, 180 MeV < E < 520 MeV). In recent years, low intensity periods were scheduled for the parity violation experiment, which used the very stable and high quality beam from the optically pumped polarized ion source (OPPIS) to achieve significant results [2]. Toward the North, the new line BL2A is directing beam to the ISAC facility. Routine proton current, at 495 MeV, was gradually increased to 40 μA. The production rate of radioactive ions was found to be nonlinear with beam current. Typical ion yields down stream of the 1/10,000 mass separator are given in Table 1, for different targets and proton currents.

After mass separation the beam, with an emittance typically of the order of 10 π mm mrad is raised vertically from the cyclotron level (264') first to an intermediate level (274'), corresponding to TRINAT (TRIUMF Neutral Atom Trap), then to the ISAC experimental hall at level 284' (Fig. 2). Here a switchyard allows the beam to be directed to the low energy experimental area [3] or toward the 0.150 to 1.5 MeV/u ISAC-I linear accelerator [4]. This was recently commissioned [5] at full power over the full energy range with different singly charged stable ions from the off-line ion source OLIS (^{4}He, ^{16}0, ^{14}N, ^{21}Ne, ^{44}Mg, ^{15}N). The RFQ is designed for ions of q/A ≥ 1/30. It consists of an 8 m long, 35 MHz, 4 rod split ring quadrupole, operating at ~80 kW cw and accelerating the beam to 150 keV/u. This is followed by a 90° MEBT stripping section and a DTL section, with five separate IH DTL tanks providing acceleration up to 1.5 MeV/u, intercalated by four magnetic triplets and three bunchers, providing transverse and longitudinal focusing. Five additional bunchers and two choppers are inserted elsewhere along the line to allow the final beam to be shaped longitudinally in bunches 85 ns apart (or 170 ns if required) with longitudinal and transverse emittance, at the maximum energy, typically of 1 keV/u ns and 0.1 π mm mrad (normalized), in line with predictions.

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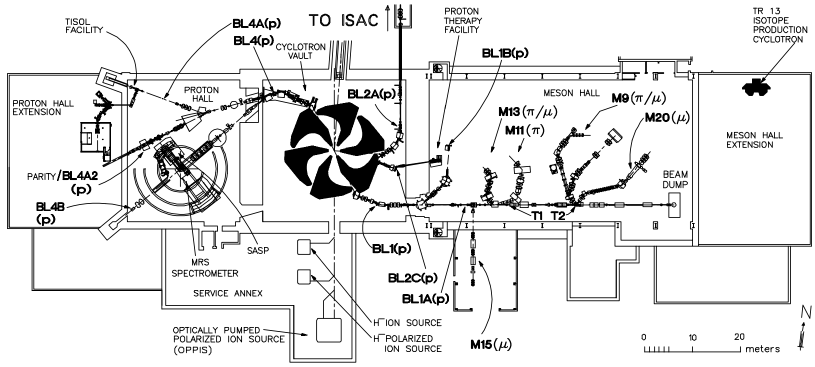

Figure 1: Layout of the cyclotron facility.

Table I: Radioactive ion yields achieved.

^{A}X	Target	Experiment	I (p) μA	Yield p/s
^{37}K	CaO	TRINAT	1	3×10^{6}
^{38}K	CaO	TRINAT	1	3×10^{8}
^{37}K	Cao	Lifetime	1	6×10^{6}
^{37}K	CaO	Lifetime	1	3×10^{8}
^{74}Rb	Nb	Lifetime	10	5×10^{3}
^{75}Rb	Nb	LTNO	10	2.4×10^{5}
^{8}Li	Nb	β-NMR	10	2×10^{8}
^{74}Rb	Nb	Lifetime	10	4×10^{4}
^{8}Li	Ta	β-NMR	20	5.6×10^{8}
^{11}Li	Ta	Yield meas.	20	1.4×10^{4}
^{38m}K	$CaZrO_3$	Lifetime	1	5.5×10^{6}
^{38m}K	$CaZrO_3$	TRINAT	1.5	1.5×10^{7}
^{21}Na	SiC	Yield meas.	10	3.3×10^{8}
^{74}Rb	Nb	Lifetime	30	8.5×10^{4}

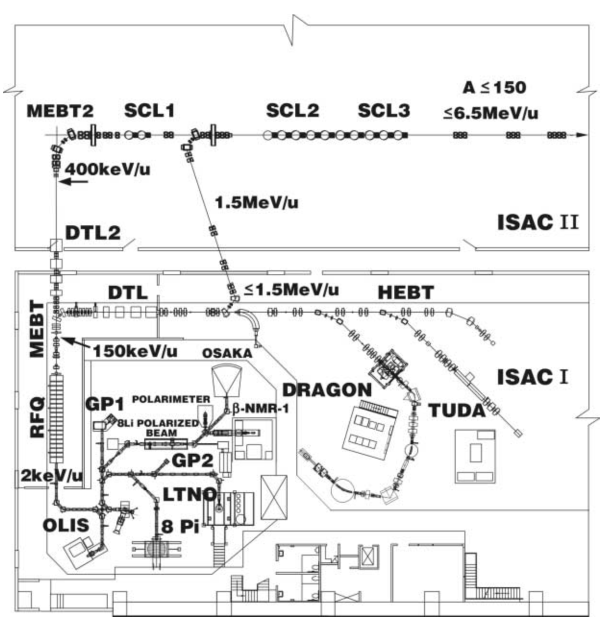

Figure 2: Layout of the ISAC-I experimental hall and the ISAC-II extension.

The ISAC-II expansion [4] was recently approved. It will allow masses with A ≤ 150 to be accelerated up to 6.5 MeV/u (and above for light ions). The expansion will include a DTL2 section extending the present 150 keV/u line to the North and accelerating the beam to a stripping energy of 400 keV/u, so that higher masses can be efficiently stripped and accelerated through the following superconducting linac. The linac will consist of low, medium, and high β sections with λ/4 cavities resonating at 70.8 MHz, 106.2 MHz, and 141.6 MHz, respectively. In order to be accepted by the RFQ, singly charged heavier ions from the ion source, with q/A ≤ 1/30, will have to be further ionized after the separator to a higher multicharge state. Both an ECR charge booster and an 11 MHz RFQ gas-stripper stage on a high voltage platform are being investigated as possible options [6]. The ECR charge booster is now being evaluated in collaboration with ISN Grenoble [7].

2 CYCLOTRON OPERATION & DEVELOPMENTS

Over the past several years the cyclotron has been operating steadily at an average 5,000 hours per year and an average 180 μA extracted beam current during high intensity periods. Beam availability in terms of hours/year (delivered vs. scheduled) was around 90%; availability in terms of average beam charge down BL1A (delivered vs. scheduled) was around 80%. An exception was year 1999 when the failure of the BL1A beam dump cooling tank brought high intensity production to a halt during a six-week period, and the availability in terms of beam charge dropped to 63% for the year.

Developments in progress are: 1) The maximum total current from the cyclotron must increase from ~200 μA at present to ~300 μA in 2003 to allow for the ISAC primary beam to be gradually brought up to 100 μA without reducing beam availability for non-ISAC users. In order to maintain cyclotron activation at present levels, the increase of H^- beam losses, caused mostly by e.m. stripping at high energy, should be avoided if possible; 2) The time structure of the extracted beam should be reduced from 4 ns to 2 ns as requested by T1 meson users.

It was demonstrated through calculations and measurements that both requirements can be satisfied at the same time by a 4th harmonic rf booster or Auxiliary Acceleration Cavity located in the space available behind resonator segments and cryopanels (AAC in Fig. 3) [8]. This will affect the energy gain per turn mainly between 400 and 500 MeV. The cavity consists of two structures attached respectively to the floor and the lid inside the cyclotron vacuum chamber. A schematic view is given in Fig. 4. In the accelerating mode, when powered to 150 kV, the booster augments the energy of particles transversing "in phase" by an additional energy gain per turn of up to 300 keV on top of the 360 keV/turn due to the fundamental rf. This reduces the time of flight in the booster region, reducing total gas and electromagnetic stripping losses, hence increasing the allowed beam intensity for a given activation. The reduction in activation was calculated to be about 33% leading to an acceptable beam increase of about 50%. The increase in energy gain per turn is also responsible for the phase compression from about 4 ns to 2 ns. The effect of the booster on a e^+, π^+, μ^+ time spectrum is shown in Fig. 5. The AAC was installed and studied during the H^- extraction studies for KAON [9]. Only recently, however, the reliability of the cavity was improved so that it could be employed for beam production.

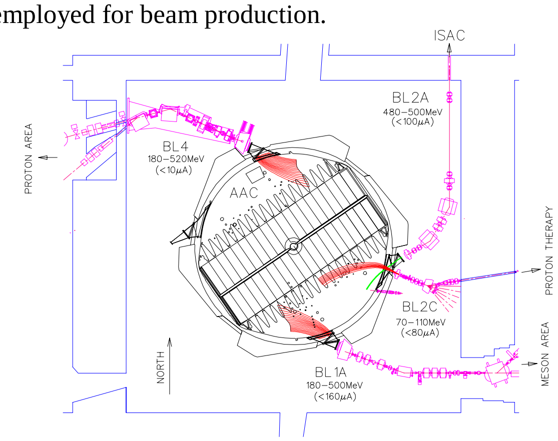

Figure 3: Layout of the cyclotron vault and of four systems for simultaneous extraction.

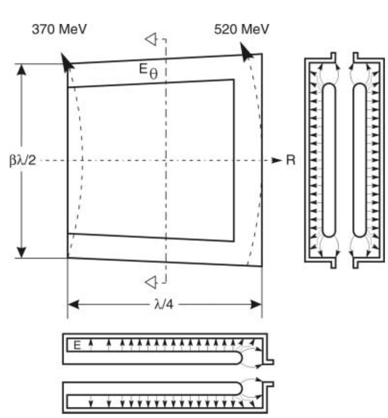

Figure 4: Schematic view of the AAC ($\lambda/4$=81.3 cm).

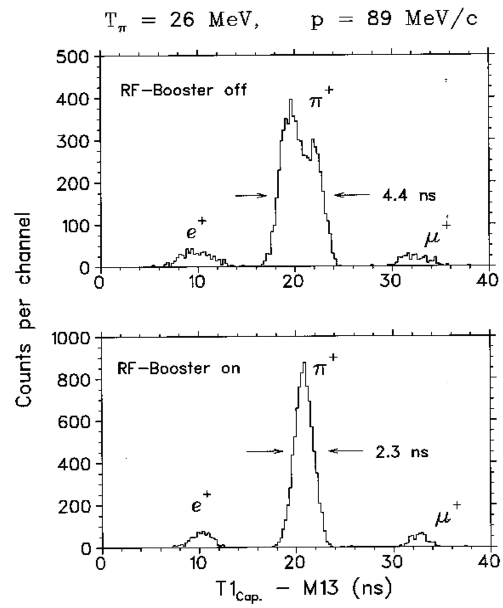

Figure 5: The e^+ π^+ μ^+ time distribution at the CHAOS detector with and without rf booster.

The major remaining limitation in achieving 300 μA is deemed to be space charge related overheating of electrodes in the center region of the cyclotron. The precise location of the beam loss has not yet been determined. Once this is done additional electrode cooling should solve the problem. A 50% pulsed beam with 400 μA peak current and 200 μA average had been accelerated to 500 MeV previously [10]. This would tend to exclude beam dynamics limitations other than the above center region beam loss.

3 REFERENCES

[1] W. Talbert *et al.*, *Development of High Power Target Concepts*, TRI-DN-00-31.

[2] A.R. Berdoz *et al.*, *Parity Violation in p-p Scattering at 221 MeV*, private communication, to be published.

[3] J-M. Poutissou, *Portrait of ISAC: The New Radioactive Beam Facility at TRIUMF*, Vol. 8, No. 3, 1998, Nucl. Physics News.

[4] R. Laxdal, *Completion and Operation of ISAC-I and Extension to ISAC-II*, Proc. PAC 2001, Chicago.

[5] R. Laxdal, *Beam Commissioning and First Operation of the ISAC DTL at TRIUMF*, *ibid.*

[6] P. Bricault, *A Charge State Breeder Based on a Low Frequency RFQ for the ISAC Accelerator Complex*, Proc. Linac Conf., Monterey, 2000, p. 211.

[7] P. Sortais, *Recent Developments in ECR Ion Sources*, Proc. Cyclotrons 2001, East Lansing, MI.

[8] G. Dutto *et al.*, *Impact of the Cyclotron RF Booster on the 500 MeV Proton Beam Production, ibid.*

[9] R.E. Laxdal *et al.*, Proc. 13th ICCA, Vancouver, 1992, p. 415.

[10] G. Dutto *et al.*, Proc. EPAC 1988, Rome, p. 32.