# RECENT PERFORMANCE OF THE TRIUMF CYCLOTRON AND STATUS OF THE FACILITY

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In December 1994, TRIUMF celebrated 20 years of operation. The peak intensity has been increased over the years to the present level of approximately 200 $\mu$A on beam line 1A. Polarized beam currents in excess of 20 $\mu$A are available although most users prefer lower intensity, higher quality slit-tailored polarized beams. The cyclotron simultaneously extracts three beams: one at 500 MeV for meson production, a lower intensity beam on beam line 4 for nuclear physics, nuclear chemistry, or astrophysics experiments, and a low energy beam (65-120 MeV, from a few nA up to 100 $\mu$A) on beam line 2C for isotope production or proton therapy. The yearly total integrated extracted beam current is now in the order of 600 mAh per year. Beam delivery is in excess of 5000 hours per year with beam availability consistently around 90%, serving as many as 8 experimental stations simultaneously. An additional simultaneous extraction line is planned for the new ISAC facility. With the present polarized beam current capability, the operation of polarized beams for the beam line 4 experiments will be possible simultaneously with the operation of the ISAC facility up to levels of 20 $\mu$A, 500 MeV, on target. Recent facility developments will also be reported.

## 1 Introduction

The TRIUMF cyclotron has now exceeded two decades of successful beam operation. Simultaneously it delivers 500 MeV proton beams up to 200 $\mu$A intensity down BL1A for meson production, lower intensity variable energy beams (between 180 and 520 MeV) down beam lines 4A and 4B for experiments with protons, polarized neutrons and unstable nuclei, and beams from less than a nA to up to 100 $\mu$A down beam line 2C at energies between 65 and 120 MeV for isotope production and proton therapy.

The facility (Fig. 1), was last described during the Vancouver conference in 1992 [1]. Since then cyclotron availability has improved to levels above 90%. The polarized beam from the optically pumped polarized $H^-$ ion source (OPPIS) has exceeded expectations. ~20 $\mu$A at about 80% polarization can now be extracted from the cyclotron. A new $H^-$ cusp source was installed in the 300 keV terminal allowing the reduction of the ripple from 20% to less than 1% with a significant reduction of the space charge dependent, time averaged, effective emittance at injection, leading to reduced losses in the cyclotron and easier tuning. The CHAOS facility for pion physics in the Meson area and SASP (second arm spectrometer) for medium and high resolution experiments in the proton area have now been completed and are in use. A high priority is a parity violation experiment relying on the OPPIS beam. This not only allows higher polarized beam intensity (which can then be tailored to provide the required beam quality), but also provides an extremely stable, fast spin-flip beam (up to 100 spin reversals per second) with negligible correlated changes in beam parameters. Other development efforts include an upgraded central control system (CCS) for the main cyclotron, a new rf control system for the main rf and a new beam stop for the high intensity beam line. The $H^-$ direct extraction program was continued to the point where the feasibility was demonstrated with an average current of 70 $\mu$A extracted in a 50% duty cycle mode at 452 MeV. The reasons for the 70 $\mu$A limit were understood and the goal of 140 $\mu$A cw extracted $H^-$ appeared definitely feasible.

Most recently a proton therapy program at TRIUMF has begun. Two patients were treated during August and September 1995 and the prospects for an important treatment center in Western Canada are now favourable. TRIUMF's technology transfer activity is also proceeding with new initiatives. A 13 MeV PET isotope cyclotron with 100 $\mu$A $H^-$ was prototyped in collaboration with Ebco Technology. A contraband detection system for narcotics and explosive detection is being defined and prototyped in collaboration with Grumman Co.

In February 1994 a newly elected Canadian government announced its decision to cancel the KAON factory proposal which had been the centerpiece of TRIUMF's future plans before 1980. Tight budget considerations prevailed, together with the realization that the laboratory should move ahead fast with a more modest but solid plan without further delays. A five-year plan was promptly submitted to the government for approval. This is based on three major efforts: 1) The construction of a new facility called ISAC (capable of at least 10 $\mu$A 500 MeV protons on target) for the production of high intensity radioactive beams and their acceleration to 1.5 MeV/n for astrophysics, condensed matter and other particle or nuclear physics studies; 2) A Canadian contribution in kind, through TRIUMF, to the LHC project in conjunction with Canada's participation in CERN experiments; and 3) Continuation of the high priority basic programs. The new plan was approved by the

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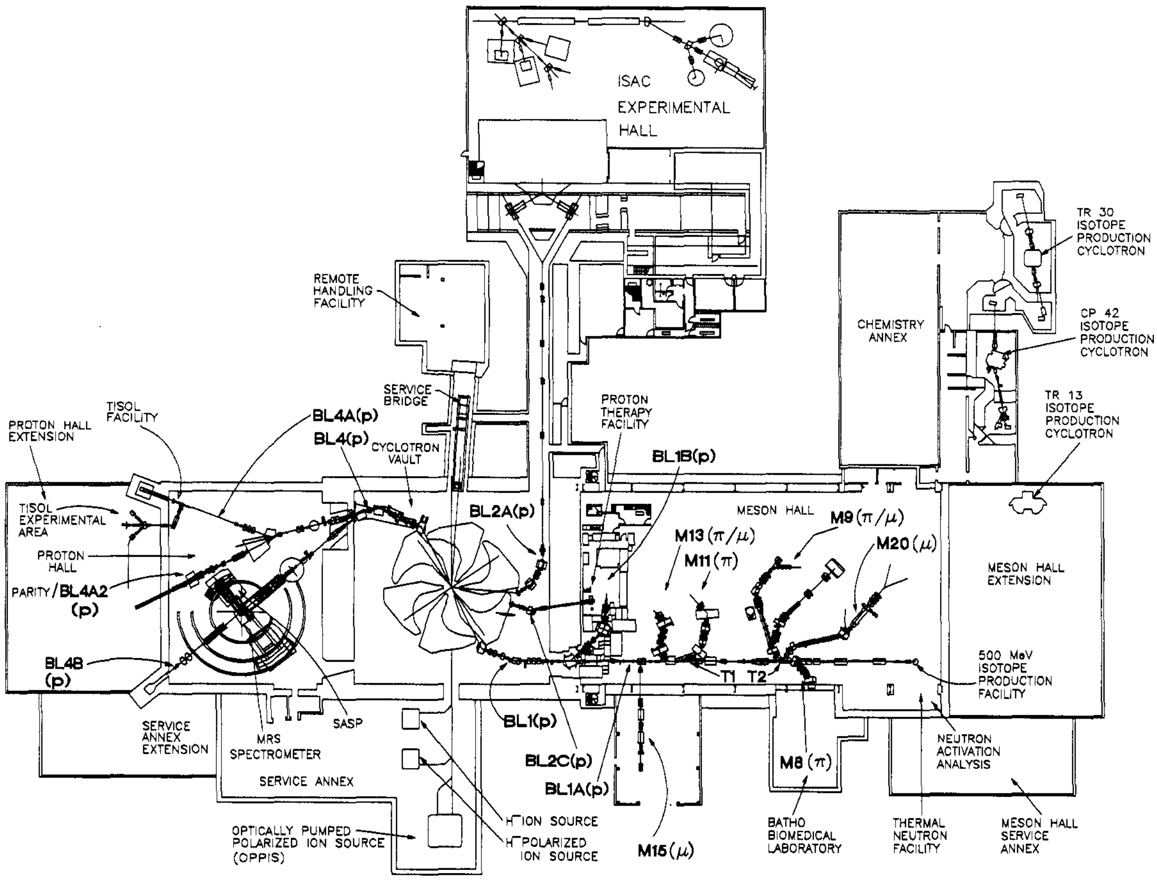


Fig. 1. Layout of the TRIUMF facility.

government on June 15, 1995 in a slightly reduced version, but for a whole five year period.

## 2 Cyclotron Performance

A typical yearly schedule of the cyclotron includes two 13 week periods of high intensity, a spring and fall shutdown of six to eight weeks each, preceded by six to seven weeks of polarized operation to allow for reduction of radiation levels. Recently, polarized operation increased to more than one third of the scheduled operation. The OPPIS was used for all polarized beam experiments.

The improved availability (consistently above 90%) was caused by a reduction in rf downtime, increased reliability of OPPIS, quicker recoveries from power interruptions and improved injection line tunes. In particular the rf controls have been replaced. The new system, VXI based, is modular in design for simplified repair and expansion. Modules include: frequency source, rf modulator, rf detector, feedback controller for rf amplitude and phase, resonator tuner interfacing to the central control system of the cyclotron, and a local controller. Digital signal processors are used as feedback compensators and major feedback parameters can be changed without shutting down the system. The local controller provides intelligence in automatically powering up the rf system.

The total beam production was increased to 575 mAh in 1994 because of an increased demand for isotope production on BL2C. Increased currents are possible because of the stable beam available from the new CUSP source and the reduced e-m stripping loss associated with the routine operation of the booster cavity [1]. Beam intensity is now limited by insufficient cooling of electrodes in the center region of the cyclotron and insufficient power handling capabilities at the BL1A target stations.

## 3 Cyclotron Development

The last extraction device to be tested for the direct $H^-$ extraction feasibility program was MC3. This magnetic channel consists of a hollow iron shunt to almost cancel the 0.56 T cyclotron field at extraction. Dipole coils are wound lengthwise to compensate the field perturbation seen by the circulating beam. The device was tested in the cyclotron in 1993. To simplify the test, measurements were made only on the internal cyclotron beam approaching the channel. The test involved powering the channel at various currents up to 110% of the design value and observing whether the beam was affected in a predictable way based on GOBLIN computer simulation studies and magnetic field calculations using POISSON. We found very good agreement between simulation and experiment [2].

A non-intercepting velocity measurement system based on time-of-flight has been installed in the injection beam line [3]. A resonant 46 MHz pick-up is positioned 3.25 m downstream of the 23 MHz buncher. The phase difference between the buncher drive signal and the modulation in the longitudinal beam density is related to the average beam velocity and hence to the energy. Relative energy shifts of $\sim 1\times 10^{-4}$ are discernible over an intensity range from 100 nA to 300 $\mu$A. The device is used to accurately reproduce the injection energy when changing from one source to another and to monitor energy fluctuations.

A proposed $\mu \rightarrow e$ conversion experiment requires a 500 MeV beam with 100-200 nsec pulses separated by 1-2 $\mu$sec with an average intensity of 200 $\mu$A. Several methods to generate such a time structure without loss of beam have been investigated [4]. In one proposal a pair of vertically deflecting plates deliver a pulsed electric field every five turns and drive a resonant coherent vertical growth at $\nu_z$=0.2 (497 MeV). Particles are intercepted by a charge-exchange stripping foil located just above the circulating beam. Simulations show that a 10 kV deflector @ 1 MHz with ~200 nsec flattop would yield almost 100% of the beam in the required pulsed time structure. A pulse generator with the above specifications and with the required rise and fall times of 40 nsec has been prepared for cyclotron beam tests.

## 4 OPPIS

The dc optically-pumped polarized $H^-$ ion source (OPPIS) has been described elsewhere [5]. For operation at TRIUMF, with its small cyclotron acceptance, the maximum performance is 200$\mu$A of 85% polarized dc current within a normalized emittance (90%) of 0.8 $\pi$ mm mrad. Higher currents are attainable at some cost in polarization. So far, up to 20 $\mu$A extraction from the cyclotron has been demonstrated. A neutron beam flux of $2.10^8$ neutrons per second from an upgraded $LD_2$ target would therefore become realistic and time reversal invariance experiments could therefore be envisaged.

The present parity violation experiment at TRIUMF requires only 0.5 $\mu$A of current extracted from the cyclotron, but has very severe requirements concerning the amount of helicity-correlated changes in beam current, energy and emittance that can be tolerated [6]. To meet these requirements, most of the source intensity must be sacrificed by using a low Rb vapour density, small ion beam diameter, no injection beam buncher, radial flag and slits in the cyclotron and a narrow extraction stripping foil. Typical source parameters in the parity experiment are 30 $\mu$A of 85% polarized current within a normalized emittance (90%) of 0.8 $\pi$ mm mrad at a Rb column density of 2.5–3 $10^{13}$ atoms $cm^{-2}$.

Figure 2 shows the primary proton extraction system (PES) on the ECR plasma chamber that constitutes the first part of OPPIS. The PES consists of three planar Mb electrodes with multiple 0.95 mm diameter apertures in a hexagonally close-packed configuration. The OPPIS current is nearly proportional to the number of PES apertures, since each aperture's primary proton beamlet results in a polarized $H^0$ beam having an emittance much larger than the acceptance of the ionizer cell. Typically a 31-aperture PES is used when running the parity experiment, but we have tried as many as 199 apertures with no loss in proportionality. The ionizer diameter is limited to 12 mm for TRIUMF operations. A 20 mm diameter ionizer with an estimated normalized emittance (90%) of 2.0 $\pi$ mm mrad at an ionizer magnetic field of 0.14 T and with a PES of 199 holes has produced a higher dc current up to 1.6 mA, at lower polarization. This high intensity source is proposed for high energy accelerators, where high power pulsed lasers would reestablish an adequate polarization around 80%.

## 5 Controls

Since 1973, the Central Control System (CCS) for TRIUMF's 500 MeV cyclotron has been driven by a group of 16 bit Data General Nova computers connected to a single CAMAC executive crate with seven parallel highway branches. In 1994 the first of these Novas

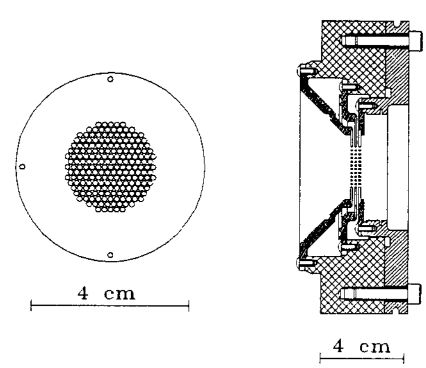


Fig. 2. ECR proton source extraction system showing 199-aperture Mb electrode.

was removed as part of a project to upgrade the CCS. VAX computers running VMS have been installed in a dual VMS cluster arrangement to replace the Novas and additional executive crates have been installed to allow expansion of the control system. By the end of 1995, the VAXes will be joined by Alpha computers also running VMS in mixed cluster configurations. Figure 3 indicates the computers arranged in two clusters, one used primarily for development purposes and the other for operation of the cyclotron. The two clusters have very similar capabilities and may be used as hot spares in cases of equipment failure. The upgrade project's schedule calls for the removal of the last of the Novas by mid 1996. A large component of the project is the operator interface. The existing knobs and buttons of the main console have been kept but the output displays are being replaced. Existing monochrome character-based displays have been replaced by colour X window terminals running the Motif window manager.

## 6 The New High Intensity Beam Stop

A new beam stop for the 500 MeV proton beam in BL1A is currently being installed (Fig. 4).It consists of a series of aluminum disks and replaces the lead TNF target originally designed as a source of thermal neutrons. Radiation levels will be much lower than with the lead target, fewer isotopes will be produced, and there will be less accumulated inventory of activity. For example, the saturated $\beta$ activity will be reduced by almost an order of magnitude. As a result, the whole target assembly and its handling systems are much simpler than before.

The new facility consists of a three piece assembly; a water vessel which is inserted into the existing vacuum tank, the aluminum target contained in the lower part of the water vessel, and a shielding plug which will be inserted into the upper part of the water vessel. The target

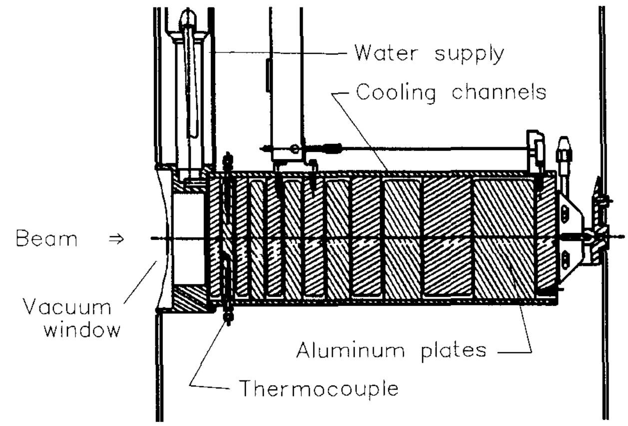


Fig. 4. The 500 MeV 200 $\mu$A Beam Stop.

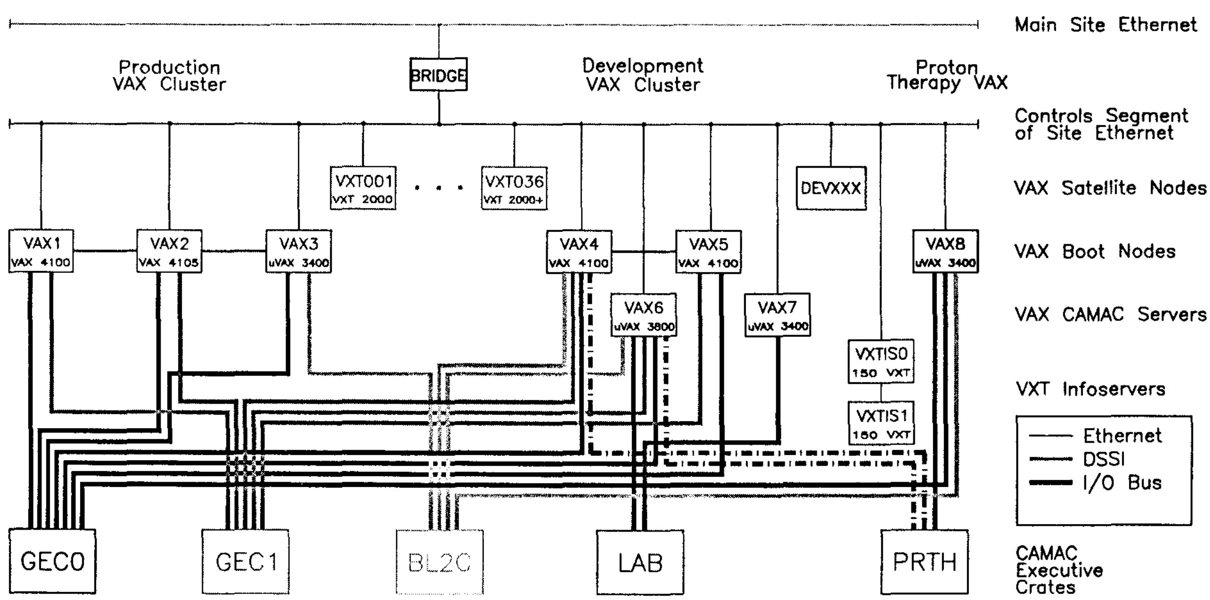


Fig. 3. Diagram of the upgraded CCS.

disks are enclosed within an aluminum can. Water flowing through the can and between successive layers of disks provides the cooling. The can is contained in a water bath for further heat removal. The water bath also acts as a neutron moderator, thereby providing some modest thermal neutron capability for sample irradiation.

## 7 Proton Therapy

In August of 1995 the first ocular melanoma patient was treated with protons with the recently commissioned Proton Therapy Facility. This facility, which makes use of the existing 65–120 MeV proton beam from beam line 2C1 (Fig. 5), is a joint project of the B.C. Cancer Agency, the UBC Department of Ophthalmology and TRIUMF. The beam delivery and patient positioning equipment follow similar designs at established proton therapy facilities. For eye treatments a beam energy of 70 MeV has been selected as optimum, with a spiral range degrader used to set the maximum treatment depth and a single lead scatterer and N/C machined modulator to spread the Bragg peak over the treatment volume.

The patient chair was designed by a local company to have six degrees of motorized control. The treatment control system is based on a Programmable Logic Controller (PLC) which controls the beam on/off device (Fast Shutter), a TRIMAC microprocessor for processing scaler information from the beam monitors, and a VAX-based system for providing display pages for the operator,

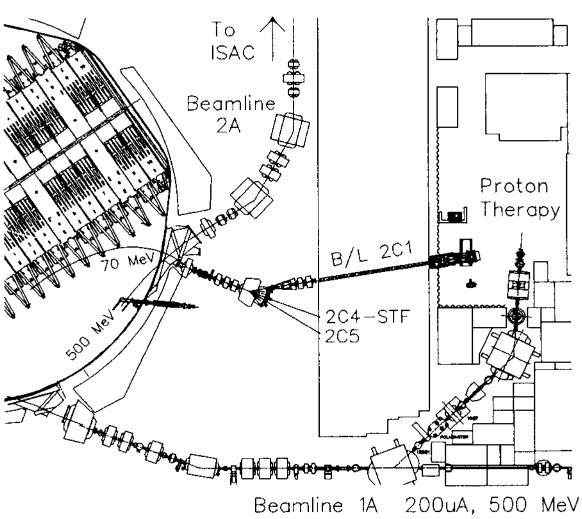


Fig. 5. Layout of the 1A, 2C, 2A extraction areas.

higher level controls such as beam scanning devices and to input patient and dose information. An independent hard-wired dose measurement system is provided as a backup. Special precautions are taken to ensure that reliable low intensity beams are delivered. During high intensity cyclotron operation a beam limiting device is used to reduce temporarily the cyclotron intensity by a factor 40. The treatment beam intensity of 5 nA is then achieved by adjusting the height of the carbon stripping wire. Measurements have indicated that the treatment dose profiles are not sensitive to the various operating modes of the cyclotron.

## 8 Isotope Production

There is increased commercial demand for the the radiopharmaceutical $^{82}$Sr produced in the solid target facility 2C4 (STF) of BL2C production. The circulating current in the cyclotron had to be increased to about 230 $\mu$A to supply 80 $\mu$A in BL2C simultaneously with 150 $\mu$A in BL1A. 77 mAh at 85 MeV with intensities up to 60 $\mu$A yielded 21 Ci of $^{82}$Sr in 1994. The STF is also being used for study of radiation damage to semiconductors and cross-section measurements of various elements for special isotopes ($^{67}$Cu, $^{103}$Pd, $^{177}$Hf, $^{177}$Lu, etc.). A molten cesium target for $^{127}$I in line 2C5 is being commissioned.

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