RELIABLE PRODUCTION OF MULTIPLE HIGH INTENSITY BEAMS WITH THE 500 MEV TRIUMF CYCLOTRON*

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Abstract

In 2001, after 25 years of smooth cyclotron operation with up to 200 μA H^- acceleration, developments towards higher intensities became compelling because of the ISAC expansion. Recently the goal of reliable total proton production current up to 300 μA, within a nominal ∼90% duty cycle, was routinely achieved. Beam availability was 90-94% over the last five years. Development highlights are discussed in the paper.

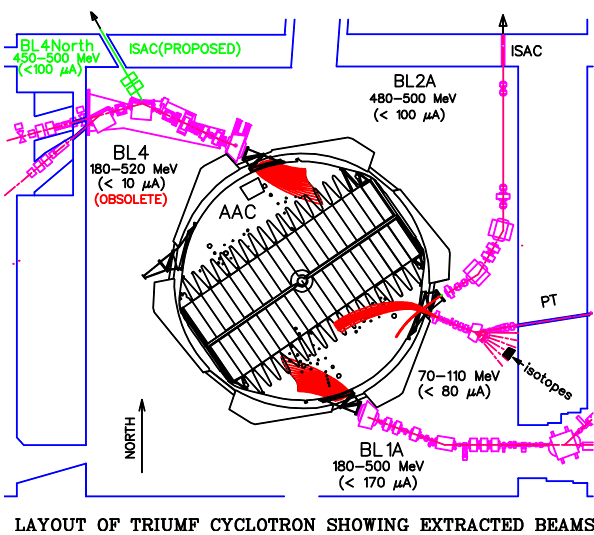

Figure 1: Layout of the cyclotron.

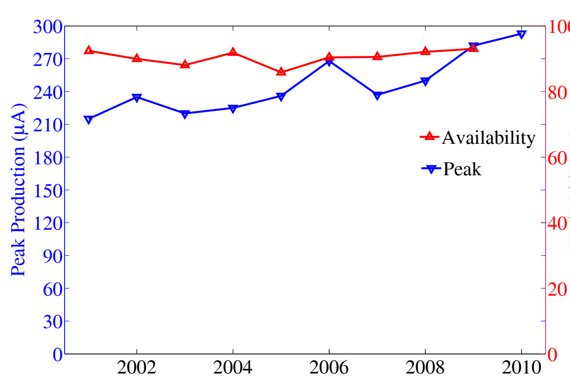

Figure 2: Peak current production and % beam availability for the last 10 years.

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INTRODUCTION

The TRIUMF cyclotron delivered increasingly intense proton beams during the past 35 years. First beam was extracted at the end of 1974. At the beginning of 1978 the installation of adequate shielding allowed up to 100 μA extraction down the meson production beamline (BL1A) (see Fig. 1). Early production and milestones were summarized at EPAC88, and a one week beam delivery test at $\sim$ 200 μA was also reported [1]. Routine beam production followed during several years up to this current level. In 1995 ISAC was approved and a second high intensity beamline (BL2A) was designed & constructed to transport a 475 to 500 MeV beam to the radioactive isotope source. In order to maintain previous production levels unaltered, it was decided to increase gradually the total cyclotron extracted current from $\sim$ 200 μA to $\sim$ 300 μA, towards a goal of 100 μA for the ISAC primary beam. Higher beam stability and reliability would also be required for this beam [2]. In 2009 a 3 hour test at 290 μA total extracted current was successfully performed. A total peak current of $\sim$ 420 μA at 25% duty cycle was also reproduced. It confirmed previous predictions of a total extracted current in excess of 400 μA [1]. It should be emphasized that reliable extraction of simultaneous multiple high intensity beams hinges on the highest efficiency, reliability and stability of cyclotrons subsystems. Recent improvements to some of these systems will be described below. Peak total extracted intensities and yearly availabilities achieved during 2000-2010 are shown in Fig. 2.

ION SOURCE

Over the years TRIUMF designed H^- ion sources for different types of cyclotrons. High current cusp sources capable of delivering up to 20 mA of H^- beam within a normalized 4RMS emittance of 0.6 πmm-mrad have been first developed for commercial isotope production machines [3]. For the 500 MeV cyclotron, where the acceptance is much smaller, the cusp source is optimized for 700 μA within a normalized 4RMS emittance of 0.1 πmm-mrad. The 12 kV ion source extraction gap is followed by a pair of magnetic steering elements, an einzel lens and iron structures to shield the beam from the $\sim$ 5 gauss main cyclotron stray field. At 1.2 m from the source, a 1 m long acceleration column takes the 300 keV beam to a 34 m long electrostatic injection line. Beam emittance figures from an 'Allison' emittance scanner located at the frontend of the line are shown in Fig. 3 for a 600 μA beam.

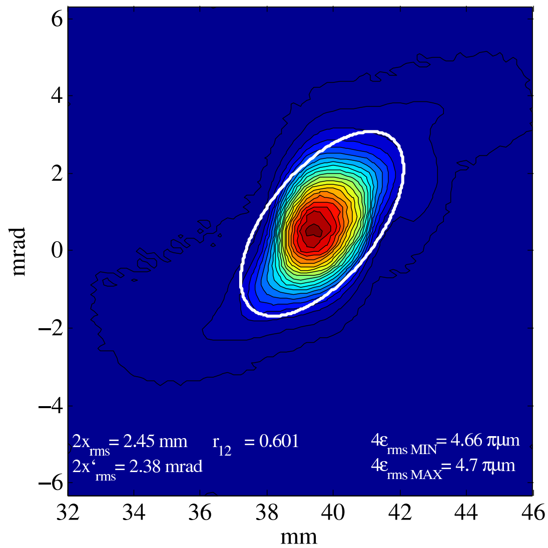

Figure 3: Emittance figure measured at 300 keV.

INJECTION BEAM LINE

The 300 keV injection line is 34 m in length and has 76 electrostatic quadrupoles. The quads are arranged in a FODO periodic lattice, with insertions for two achromatic $2 \times 45^{\circ}$ electrostatic bender sections, a slit section for pulsing and matching sections to match from the ion source to the lattice, and from the lattice to the cyclotron. Diagnostics consists of 13 scanning wire profile monitors, and a number of cooled apertures and beam stops. The full 600 μA is transported to a set of slits in the periodic section, separated by 90° of phase advance. Adjusting the slits allows transporting zero to the full 600 μA beam current without adjusting the ion source. Besides halo-cleaning, this technique has the advantage that the emittance is the smaller, the smaller the required beam current.

For large currents, it is especially important to match the beam to the periodic section. This has been accomplished by measuring the beam profiles at a number of scanning wire diagnostic stations and fitting to find the beam's Courant-Snyder parameters. A tune for the matching section (see Fig. 4) was then calculated using the TRANSOPTR computer code [5]. The recently installed Allison-type emittance scanner has greatly simplified the matching exercise.

After a further 12 m of travel, the beam is bent downward towards the cyclotron. The vertical section is 13 m long and has only two scanning wires so matching is difficult to verify. Bunchers are needed to match the DC beam to the 40° cyclotron phase acceptance. These are placed 20 m from injection (partway along the horizontal section), so the 600 μA reaches a local peak current of approximately 5 mA at the end of the injection line. The large resulting space charge forces, plus the axial magnetic field from the cyclotron and lack of diagnostics make it difficult to model the beam optics accurately.

As the vertical section has operated continuously since

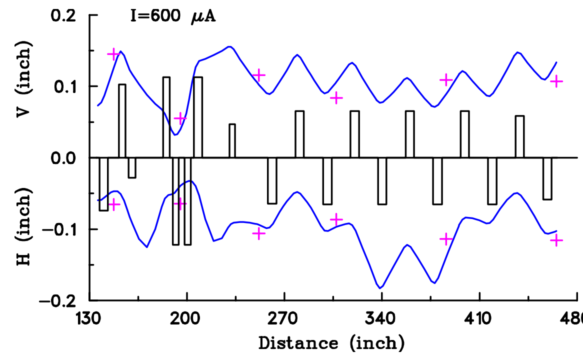

Figure 4: Calculated envelopes and measured beam sizes show good agreement in a periodic section at 600 μA. Vertical rectangles represent quadrupole focus strengths.

1975, some of the insulators of the electrostatic optics have accumulated sufficient quantity of cracked hydrocarbons and other debris that reliability is being threatened. The optic elements in question are deep inside the support structure of the cyclotron so mitigation by simply cleaning the insulators is not an option. For this reason a new vertical section has been designed and built and will be installed in Spring 2011. To design the optics, TRANSOPTR was expanded in capability to calculte beam envelopes including the effects of bunching, space charge, coupling from the axial magnetic field and the electrostatic spiral inflector, and rf acceleration in the cyclotron. Details can be found [4]. The resulting design is significantly simpler with 5 rather than 9 matching quads. As well, the new line will have 5 scanning wires and capacitive longitudinal (bunch shape) and transverse (BPM) monitors.

CENTRAL REGION

The central region was extensively studied during the cyclotron design stage [6]. This resulted in a magnetic field bump in the centre having the effect of moving the beam phase interval from negative to positive (lagging) phases during the first few turns and back to zero later. Simulations also showed a significant phase bunching effect on the first turn due to magnetic and electric field configurations. The central electric field configuration remained unaltered over the years. Beam deflecting or collimating electrodes were inserted in field-free regions. The magnetic field configuration can also be partially affected by tuning the inner trim coils: trim coil zero in particular. In order to be able to raise beam intensity and reduce losses in the central region, several systems had to be thoroughly refurbished.

These included the two low energy probes which had to be used to measure radial and vertical beam distributions. As these probes are completely inside the vacuum tank and repairs require tank lid opening, their use demands a very high level of reliability. Also, interfering rf leakage had to be reduced significantly or eliminated. Thanks to excellent work by the diagnositc and rf groups the required reliability was achieved.

The electrostatic correction-plate system [7] was also overhauled. This system and its vertical protection beam scrapers, extending radially on opposite dee segments to about 1.25 m from the centre, where vertically realigned (within ~ 1 mm), to allow thermocouples to warn of small beam losses that could otherwise damage plates or wireways.

Recent additions include: (1) a cooled absorber inserted in the beam within the first quarter turn, to prevent unwanted injected ions from overheating stainless steel structural supports; (2) radial flags attached to the central vertical dee walls on the second and forth quarter (3) thermocouples on uncooled electrodes close to the beam.

Under optimal conditions transmission up to 70% has been measured between the lower end of ISIS and the total extracted current. Taking into account outer beam losses caused by vacuum and electromagnetic stripping one concludes that the centre region can accept over 75% of the ISIS beam. Extracted beams have good spot sizes at the targets and a $\sim$ 5ns time structure. We expect that the imminent installation of a new vertical injection line with optics more favourable to higher space charge will allow significant progress above 300 μA total extraction [8].

OUTER REGION

The TRIUMF cyclotron is operating with the two high energy strippers in "shadow mode". The meson production beamline (BL1A) and the radioisotope production beamline (BL2A) are one sector (60°) apart. To set up, the BL1A stripper is moved radially inward to initially extract all the beam, then the BL2A stripper is moved radially inward by steps of a fraction of a mm until the desired split ratio is obtained. Slight changes in the circulating beam orbit due to small changes in, for example, rf voltage can cause a large fluctuation of the split ratio of beam currents between BL1A and BL2A. The reason is that the radial density contains strong modulations that originate from the $\nu_r = 3/2$ resonance at 428 MeV. This modulation starts at 428 MeV and persists to 500 MeV extraction. Monte Carlo simulations and measurements with a high energy probe with a radial differential head have demonstrated such an oscillation in the beam density [9]. In principle, the modulation can be eliminated by correcting the resonance; this requires a third harmonic in the magnetic field gradient. Unfortunately, though there are harmonic coils, these were only designed to generate a first harmonic: there are 6 coils, one per sector. Powered as a third harmonic, the phase is fixed except that they can be reversed in sign for a 180° shift in phase. Thus we could only obtain a partial compensation for this resonance, reducing the beam density oscillation by $\sim 40\%$. Measurements are shown in [9].

EXTRACTION AND BEAM STABILITY

Several improvements were made to get the required higher stability for the ISAC primary beam. First, the BL2A stripper current was stabilized by installing a feedback loop between the stripper and the pulser at injection, regulating the beam's duty cycle. Decreases in the stripper current are compensated by increases in duty cycle and vice versa [10]. Second, automatic beam steering was implemented to keep the beam centred on target. Thirdly, the 2A beam line tunes were developed to image at the target the spot at the stripping foil, thereby minimizing the beam halo on target. Automatic beam steering was also implemented for all targets in BL1A.

Developments in extraction foil materials and technology have resulted in improved beam quality and stability. Highly-oriented pyrolytic graphite is now used as stripping material, mounted in a tantalum frame with a thin copper cushion. Additional heat relief features were introduced. These changes have resulted in lifetimes extended from the typical $\sim$ 65 mA-hr to over 250 mA-hr for the most recent BL1A foil, operating at 140 μA and 480 MeV with negligible release of ^{7}Be contamination. BL1A and BL2A extraction foils are now 1.5 mg/cm^2 thick instead of the previously standard 5 mg/cm^2, and are 32 mm tall by 0.25 to 16 mm in radial width for partial or full stripping extraction. BL2C utilizes carbon wire strippers as single filaments for extraction of low intensity beams for treatment of ocular melanoma, or filament curtains for high intensity operation (70 μA) for the production of radiopharmaceuticals.

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