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ACCELERATOR DEVELOPMENTS AT TRIUMF

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Abstract. The 70 - 520 MeV TRIUMF cyclotron continues to run with ~90% availability, delivering high-intensity unpolarized beams (up to 200 μA) and 80%-polarized beams (up to 10 μA) to users for 8 to 9 months per year. The optically-pumped polarized H^- source gives dc beam currents above 200 μA and is being developed to provide very stable beam characteristics for high-precision experiments. Prototyping of the H^- extraction system is now complete and beam tests have demonstrated its feasibility with a 70 μA cw beam. Upgrades are under way on the controls and some other systems, and a proton therapy facility is being commissioned. Three small H^- cyclotrons (42 MeV 200 μA, 30 MeV 500 μA and 13 MeV 100 μA) are now in regular operation for isotope production, the latter two having been recently designed and built at TRIUMF in collaboration with Ebco Technologies Inc. Development of the existing TISOL radioactive beam facility is proposed, based on upgrading the present source, fed by a 10 μA proton beam, and installing low-beta RFQ and interdigital drift-tube linacs to accelerate light ion beams (A<30) to 1.5 MeV/u. It is also proposed thatTRIUMF take responsibility for a Canadian contribution "in kind" to the Large Hadron Collider (LHC) at CERN. The first stage would involve collaboration with CERN in upgrading the injector chain (PS Booster, PS and SPS).

Introduction

In two months' time, on December 15, TRIUMF will celebrate the 20^{th} anniversary of the first acceleration of beam to 500 MeV in the H^- cyclotron meson factory. For many years now the cyclotron has operated well over its original target specifications, supporting a 750-strong user community in nuclear, particle and condensed-matter physics, chemistry, pharmaceutical sciences and medicine—a community recently strengthened by the participation of scientists from various centres in the former Soviet Union. This strong scientific interest is driving major improvements in cyclotron performance, as will be described below, and in the experimental facilities. The latter include the second-arm spectrometer (SASP), working in concert with the MRS spectrometer so that two reaction products can be analyzed simultaneously; the CHAOS spectrometer for pion scattering and reactions; the TISOL facility providing low-energy radioactive ions for nuclear astrophysics; and a proton therapy facility to complement that which has provided pion treatment to 340 patients so far.

Technology transfer to industry has become an important activity in the last few years. Two accelerator activities will be described—the development of small cyclotrons for isotope production and of a high-voltage accelerator for an explosives detector.

The cancellation of KAON by the new Canadian government earlier this year has led to a reassessment of TRIUMF's future, and to the formulation of a Five Year Plan proposing two major new projects. The first of these, ISAC-I, would add an RFQ and linac to TISOL to provide 1.5 MeV/u radioactive ion beams. The second would be management of a Canadian contribution to the CERN LHC, particularly upgrading the performance of the injector chain. TRIUMF is also collaborating in national studies of a Canadian synchrotron light source.

Full details of all these activities may be found in the proceedings of recent accelerator conferences(1-3).

520 MeV Cyclotron

Over the last twelve months the cyclotron has continued to operate very reliably, delivering beam for 94% of the scheduled 5141 h, the charge delivered amounting to 432,570 μA h, 100.3% of that scheduled. The 500 MeV unpolarized production beam normally runs at 150 - 160 μA, while two simultaneous beams are provided for proton-induced reactions or TISOL (about 1 μA at 180 - 520 MeV) and isotope production or proton therapy (up to 50 μA at 70 - 110 MeV). To supply the required H^- beams, high-brightness dc cusp sources have been developed to give as low as possible an emittance for a given current (e.g. 0.35 πμm, normalized, at 5 mA, the maximum current being ~12 mA).

Polarized proton beams (up to 10 μA with 80% polarization) are run for ~30% of the scheduled time. While LAMPF and PSI provide more intense unpolarized beams, TRIUMF's continued development of optically-pumped polarized sources, in collaboration with INR Moscow, provides the most intense polarized proton beams at any meson factory. Injection line tests have demonstrated 56 μA with 85% polarization and 120 μA with 78% within a normalized emittance of 1.0 πμm; over 200 μA have been observed with higher emittance. This high performance is the result of improvements to the ECR proton source and optimization of the rubidium vapour optical pumping cell.

The stability requirements on the source are very high, driven by a parity non-conservation experiment which aims to measure the longitudinal analysing power A_z in $\vec{p}-\vec{p}$ scattering to 2 ± 10^{-8}. The tolerances required on helicity-correlated changes in beam current ($\pm 10^{-5}$), energy (± 0.5 eV), position (± 5 μm), and width (± 0.05 μm) have been realized on an individual basis.

The tuning of the polarized beam through the cyclotron has been greatly simplified by the installation of a variable-duty-factor chopper in the 300 keV injection line. This provides 6 kV pulses at frequencies of 1 – 20,000 Hz, and allows time-of-flight measurements to be made to optimize the magnetic field and isochronism.

The 92 MHz fourth-harmonic booster cavity is now operating on a routine basis at 120 kV, after resolution of some power amplifier and rf leakage problems. This increases the energy gain per turn from 320 keV to 560 keV in the 370 – 520 MeV range while reducing electromagnetic stripping losses from 8% to 5% and the tank activation by about one third.

Development of an extraction system for H^- ions (rather than protons) was completed by the installation and testing of a current-compensated iron-core magnetic channel. Beam tests confirmed that the ions circulating at smaller radii were unaffected by the channel when the coils were correctly excited.

A major upgrade is under way to the central control system, involving progressive replacement of the ancient Nova computers by VAX systems. Progress is also being made in developing object-oriented software for device access.

Technology Transfer

Transfer of technology to industry is a rapidly growing activity at TRIUMF, with many new initiatives under development. Two major ones involve accelerator technology. The first of these is a collaboration with Ebco Technologies, Inc. for the design and prototyping of small commercial cyclotrons for isotope production. The first prototype, the TR30, has been operated by Nordion Inc. at TRIUMF for the last four years, providing 500 μA H^- beams at selected energies between 15 and 30 MeV. Its operation has been highly reliable and it is responsible for 80% of Nordion's production, worth $15 million/year. TRIUMF is currently collaborating with Nordion to upgrade this machine for 1000 μA operation. A second machine, the TR30/15, has been in operation at INER in Taiwan since June 1993. This produces

150 μA D^- at energies up to 15 MeV, in addition to 400 μA H^- up to 30 MeV.

The prototype of a smaller cyclotron, the TR13, designed specifically for PET radioisotope production in hospitals, is currently making its first production runs at TRIUMF for the UBC PET centre. It delivers 100 μA H^- to 13 MeV and has been operated at low currents to 19 MeV (the shielding is designed for 13 MeV). The first production model TR13 has been shipped to Seoul State University and is currently being commissioned.

The second major activity is development of an explosives detector based on resonant γ-ray absorption by ^{14}N. The γ-rays are produced through the $^{13}C\,(p,\gamma)$ reaction using a 2 MV tandem and 10 mA H^- source. The detection system has been successfully demonstrated on an existing accelerator and TRIUMF is currently collaborating with a commercial partner in the first phase of a project to build a working model.

KAON

In February 1994, the newly-elected Canadian government announced its decision to cancel the KAON Factory(4), which had been the centrepiece of TRIUMF's future plans since the late 1970s. This was a dramatic reversal of fortune following the election defeat of prime minister "KAON Kim" Campbell, and a lesson in the vulnerability of scientific projects large enough to require political backing. Only a month earlier, a meeting of KAON "participation panels" from different countries had concluded that more than $500M of the $708M (Canadian) capital cost had been approved—$236M each from Canada and British Columbia, and $30M from Germany, France and Italy, with prospects of further contributions from these countries, the USA and Japan upon confirmation of support by the new Canadian government. Russia was also expected to contribute through manpower and favourably-priced hardware through collaborations with INR Moscow and INP Novosibirsk.

Technical progress had been made in a number of areas prior to cancellation. One of these was the search for compatible racetrack lattices for the 450 MeV Accumulator and 3 GeV Booster rings, located in the same tunnel. The design aims included high γ_t, dispersion-free long straights for rf and beam transfer, dispersive straights for H^- injection and momentum collimators, shape compatibility, good dynamic aperture, insensitivity to space charge and polarization friendliness. The lattices chosen use missing-bend FODO cells in the arcs, with four of the D quadrupoles in the Accumulator split and separated to provide dispersive straights suitable for H^- injection. Other beam dynamics topics have included simulation studies of reconstructing lattice optics functions from orbit measurements, methods for finding bunched-beam instability thresholds, and large-amplitude stability criteria for beam-loaded rf systems.

Development of the 65 kV 46 – 61 MHz Booster cavity has been concluded with successful full-scale tests of a higher-order-mode damper, in the form of a five-element coaxial high-pass filter. The damper consists of a three-gap disc structure at the accelerating gap, shielded from the beam by a coaxial "horn". With a corner frequency of 126 MHz all nodes up to 700 MHz were satifactorily damped with negligible effect on the fundamental. The RF Group has also collaborated with INR Moscow and Salut in development of a magnetron-like varactor tuner. Power level tests confirmed its viability as a narrow-range tuner for moderate to high-voltage cavities. An important feature is its very rapid response time (1 μs).

The Kicker and Chopper Group has concentrated on improving the pulse shapes from these devices. A combination of saturating ferrite at the kicker input and speed-up network at the output proved very effective, reducing the 1% to 99% field rise time to 62 ns and improving the flat top.

Future Plans

With the disappearance of KAON a Five Year Plan has been developed, based on building the first stage of the ISAC radioactive beam accelerator and managing the proposed $50M (Canadian) contribution "in kind" to the Large Hadron Collider at CERN. The latter programme would mainly be directed to the upgrades required to the injector chain (PS Booster, PS and SPS), taking advantage of the experience of high intensity machines in this energy range developed for KAON. To achieve the time structure and luminosity desired for the LHC requires new rf systems on each machine and an increase in the PSB energy to 1.4 GeV. Canadian involvement is expected in rf systems, magnets, power supplies, kickers, beam dynamics, instrumentation, and controls.

The proposed ISAC radioactive beam accelerator would consist of a 150 keV/u RFQ linac, followed by a stripper and a series of independently-driven interdigital-H (IH) rf structures. The Five Year Plan would take this to the 1.5 MeV/u stage, with installation on the existing 10 μA proton line, together with an upgraded ion source and separator. This would provide five to ten times more production beam than any similar facility and could deliver beams of A< 60 radioactive ions at unprecedented intensities (3.6×10^{10}/s/mb).

Since the charge to mass ratio of the ions is very small ($q/A \geq 1/30$) the RFQ must be operated at very low frequency. This is a major technical challenge, especially as a cw operating mode is preferred to preserve beam intensity. To achieve a reasonable cavity diameter at the chosen frequency

of 35 MHz, a four-rod zero-mode structure is used. A number of four-rod structures have been investigated in model tests, the best being found to be a split-ring design. With this, a shunt impedance of 265 kΩ/m has been achieved and 500 kΩ/m is believed within reach. The injection energy would be 2 keV/u, the inter-electrode voltage, 100 kV, and the length 9 m.

The post-stripper linac will be composed of four IH structures driven independently in order to provide continuous energy variation. These cavities will be operated at 70 MHz, quadrupole triplets being placed between each tank for transverse focusing.

Looking beyond the Five Year Plan, a number of accelerator projects are being considered. One that has wide-ranging support across the Canadian science community is for a Canadian synchrotron light source. The Canadian Institute for Synchrotron Radiation has been promoting a Canadian source for some years and has recommended "a world-class machine in the 1.5 – 2.5 GeV range, with some provision for x rays." In line with this, we have selected the Swiss Light Source as a reference design. This is a 1.5 – 2.1 GeV design providing a very low emittance (1.6 nm-rad) operating mode, with up to six superconducting dipoles to produce hard x rays, and two very long straight sections for advanced insertion devices. With the collaboration of PSI we have investigated some similar lattices giving eight and ten straight sections instead of the original six. Initial studies show that the good optical properties of the SLS can be preserved in these new lattices. The future of this initiative will depend strongly on the result of a current government enquiry into Canada's need for synchrotron light sources and spallation neutron sources for materials research.

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