40 YEARS ON – REFLECTIONS ON THE HISTORY OF TRIUMF FROM CONCEPTION TO THE FIRST BEAM

BY MICHAEL CRADDOCK

This retrospective is a compendium of a ten-article series entitled "40 Years On" written by Michael Craddock between 2006 and 2015. Michael passed away on November 11, 2015, five months after penning the last article

FORTY YEARS ON - TRIUMF'S BEGINNINGS IN 1965

By the 1960s, under the inspired leadership of John Warren and George Griffiths, the UBC Nuclear Physics Group had produced more than half the Canadian Ph.D.s in that field. But the 3 MeV van de Graaff accelerator, built by John and his students in 1948, no longer provided the exciting research opportunities of higher energy machines being built at universities across the country. Ottawa was believed to be sympathetic, but tight-fisted, as its rejection of a 1960 UBC proposal for a 12 GeV proton synchrotron had shown. John therefore proposed a joint project with B.C.'s two new universities, Victoria (1963) and Simon Fraser (1965). But was it to be aimed at nuclear structure or particle physics? There was a wide split between low and high energy enthusiasts — with John writing in March 1965, "I would not settle for less than 3 GeV". As the junior dogsbody, I was then delegated to look at some recent U.S. proposals. It became clear that such energies were too costly, but that a meson factory might not be, and could satisfy both camps.

Astonishingly this notion was approved unanimously at a meeting of the UBC nuclear physicists in May 1965. The name TRIUMF (Tri-University Meson Facility) was coined soon after, and the TRIUMF Study Group was formed, with University of Victoria (UVic) and Simon Fraser University (SFU) members, to formulate a request for funds to produce a full proposal. A fully-fledged meson factory seemed too ambitious, particularly the shielding challenges, so we aimed only at a stripped-down 500 MeV, 20 mA "Meson Workshop". A powerful new UBC arrival was Erich Vogt, and with John away on sabbatical, he led the Group in compiling *The TRIUMF Project* report.

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SUMMARY

This article is a collection of articles meant to reflect the history of TRIUMF from its first beam. Beginning in 1965 through to 1974, it provides an insider's look at how TRIUMF came to be.

Of the various designs extant, I had recommended Reg Richardson's UCLA H^- cyclotron as potentially the most flexible and least expensive. Extensive consultations confirmed that it was a safe choice, and we persuaded Reg that we were competent to foster his baby — the deal sealed by a visit to UCLA by George Griffiths, Karl Erdman, and myself on December 15th, where we also negotiated the loan of their 1/20 scale model magnet. Oddly enough, this was *nine years to the day* prior to achieving the first 500 MeV beam at TRIUMF!

1966: ASSEMBLING THE TEAM

The newly formed TRIUMF Study Group spent the fall of 1965 compiling their initial *Report on the TRIUMF Project,* and early in January 1966 it was submitted to the Atomic Energy Control Board (AECB), the agency then responsible for funding university nuclear physics research. In April a $100,000 grant from Ottawa was obtained, enabling us to hire staff and purchase equipment for model design and cost studies.

The first TRIUMF employee was Joop Burgerjon, who brought considerable experience from building cyclotrons in Amsterdam, Pretoria, and Winnipeg. One of his first contributions was designing the original TRIUMF logo. In September he was joined by Ed Auld to work on the cyclotron magnet design. The loan of a 1/20-scale model magnet by Reg Richardson and his UCLA colleagues and the purchase of a 150 kW, 3000 A power supply enabled a complete test setup to be assembled by the end of the year. Orbit studies of the sensitive central region were initiated with the help of a computer analyst, David Scott. Additional civil and mechanical design was provided by Terry Creaney *et al.* of Shawinigan Engineering, who also compiled the initial cost estimate — $22 million in 1966 dollars (at least $140 million today).

The end result was the *TRIUMF Proposal and Cost Estimate,* edited by Erich Vogt and Joop Burgerjon, submitted to the AECB in November, which recommended a full 100 µA meson "factory". This required a larger machine: orbit radius now 271″ from 230″, and magnet weight now 2800 from 1470 tons. The initial plan was for one extracted beam with all experiments in one hall at the proposed site on the south end of the UBC campus.

A crucial advance in 1966 was the informal involvement of the University of Alberta. Several members, led by Jack Sample and Croy Nielsen, joined the TRIUMF Study Group, and the *Proposal* included a statement from the UoA's Board of Governors approving in principle the university's participation. Interestingly, one of the conditions set was that "The name of the project would need to reflect the University of Alberta's place as a founding partner". I recall giving a talk in Toronto at that time entitled "The TRIUMF-AL Project" — but somehow the suggestion didn't catch on!

1967 — WORKING ON THE TECHNICAL DESIGN

With the *TRIUMF Proposal and Cost Estimate* submitted in November 1966, TRIUMF's small team of physicists and engineers, guided by the TRIUMF Steering Committee (John Warren, Erich Vogt, Joop Burgerjon, Brian Pate, Mike Pearce, and Jack Sample), was able to concentrate on optimizing the design through calculations and model studies. The $100,000 grant received from the AECB in 1966 was renewed in April 1967 but didn't provide much for increasing manpower, though we were able to hire our first summer ("Miss I. Hor and Miss J. Argyle") and first graduate (Sherman Oraas, Robin Louis, and N. Al-Qazzaz) students.

The major effort, led by Ed Auld, focused on the cyclotron magnet, the largest and most expensive component. The equipment built to survey the UCLA model magnet worked smoothly, and tests were made of various shapes for two neighbouring sectors and different coil configurations. But no arrangement seemed capable of providing sufficient magnetic field drop-off between the sectors to maintain vertical focusing at the highest energies, leaving only one solution — increase the 500 MeV radius from 271" to 302".

The radiofrequency (RF) effort, led by Karl Erdman, centred on the construction and testing of a ¼-scale resonator section model — the first in TRIUMF's cost-effective tradition of plywood and copper-sheet RF cavities. One important result confirmed that the coupling between top and bottom resonators was strong enough that feeding RF into one was sufficient to excite the desired standing waves in both.

My studies on the central region focussed on the spiral inflector and the RF accelerating gaps — the latter because their strong focusing effect in a region with minimal magnetic focusing is crucial in determining how much of the incoming beam will be captured. Field computation codes were still primitive, so a copper model was constructed and shipped to the Maryland cyclotron for measurement. Thankfully, orbit studies based on the fields obtained showed that ions passing through the first gap would make it around the centre post, though centring was difficult.

Led by Mike Pearce, studies into the design of the extracted proton beams were initiated at UVic. This involved developing a hybrid analog computer and writing their own tracking and optimizing codes!

Perhaps the most significant development for the future was the UBC Board of Governors' approval of the present 6.6 acre site, in place of the 4 acre one across the road previously assigned.

1968: FEDERAL FUNDING APPROVED!

On April 16th, 1968, federal funding for the TRIUMF project — about $20 million over six years — was announced by the Hon. Jean-Luc Pepin, Minister of Energy, Mines and Resources. Discussions in Ottawa through the winter raised expectations and in January the AECB indicated (unofficially) that the $1.3 million first-year construction funding was to be approved, and so a Board of Management with members appointed by the four universities could be set up.

The Board first met on March 2nd, when it appointed a Director (John Warren), Associate Director (Erich Vogt), and Chief Engineer (Joop Burgerjon), and established a monthly Operating Committee meeting to represent the interests of the university users. We considered ourselves very fortunate to have succeeded within three years of the project's conception, given the economic downturn at that time, and that Chalk River's $150-million proposal for a 65 mA 1 GeV Intense Neutron Generator was turned down.

Funding for the buildings was a local responsibility, and when the B.C. government refused to provide direct support, we were again fortunate that the three B.C. universities agreed to allocate a significant fraction of their building funds — around $4 million — to TRIUMF. The University of Alberta contributed $1.25 million in experimental equipment.

Meanwhile, the detailed design was progressing: the latest magnet model had extended the stable orbit region up to 440 MeV; tracking showed that ions emerging from the spiral inflector over a wide range of initial energies could be steered into centred orbits; measurements on a ¼-scale model cavity provided important data on RF power loss; a model vacuum chamber was under construction; and the engineering consultants provided draft design reports on the buildings and the magnet support structure. But the best news was undoubtedly the arrival of the first cheque ($650,000) by surface mail!

1969: TRIUMF MOVES INTO HIGH GEAR

In April 1969, TRIUMF began a period of rapid expansion. In one year, 22 new hires joined the original 9 staff (see Fig. 1 for a staff photo in spring 1968). A Project Management Office led

Fig. 1 The TRIUMF staff on the site of the future TRIUMF laboratory, June 1968.

by Terry Creaney was set up with staff from the Shawinigan and Montreal Engineering Companies. Building and Safety Committees were created, and engineering firms contracted for detailed design of the buildings, cyclotron, and ancillary equipment. User Groups (Proton, Meson, Slow Neutron, Radiochemistry, Radiobiology & Radiotherapy) were formed to represent the experimenters' interests.

Design modifications to the magnet model had extended the focused-beam region out to the full 500 MeV, and a special model had been built to study the central-region field. A new tape-controlled milling machine in UBC's Mechanical Engineering Department confirmed that the spiral inflector electrodes could actually be built. RF studies were performed on ¼-, ½- and (partial) full-scale models of the resonators, tests of 20K cryopumping began, and a 1/20-scale vacuum chamber model was built for outgassing and other studies. A beam transport system was designed for the extracted proton beam allowing pion-production targets up to 20 g/cm^2 thick.

A critical step was completing TRIUMF's first physics experiment — a measurement at the Rutherford High Energy Laboratory in England of the H^- ion's lifetime in the electric fields induced by passing through magnetic fields at relativistic speeds. The lifetime was found to be only one-third of the theory prediction and previous less-accurate measurements! To keep high-energy beam losses below 6% as planned required a 4% reduction in magnetic field strength, increasing the outer 500 MeV orbit radius to 312" — and raising the cyclotron's cost by about $430,000.

Twelve months of intense activity culminated in the official dedication of TRIUMF on May 5th, 1969 by federal Minister Jean-Luc Pépin (see Fig. 2). The site remained an empty field but for the office building's skeleton, so the ceremony was held at the traffic circle outside. The proceedings ended with the planting of a scion of the apple tree from Isaac Newton's home, a symbol to inspire TRIUMF scientists to equally great insights. After forty years, there are now seven trees thriving there and anyone is welcome to pick "Newton apples" in the Fall.

1970: EXCAVATIONS COMPLETE AND CRM CYCLOTRON TAKING SHAPE

The year following the official dedication saw tangible progress across the lab. By June 1970 the staff had grown to 43, not

Fig. 2 UBC Chancellor John Buchanan looks on as federal Minister Jean-Luc Pepin plants a scion of a Newton apple tree at the official TRIUMF dedication, May 5, 1969.

counting university people, with another 12 at UVic, 5 at SFU, and 6 at Alberta. The skeletal Office & Laboratory Building was completed over the summer and fully occupied by November.

Outside, the muddy field was transformed by heavy earth-moving equipment, and employees enjoyed the spectacle of great fountains of water shooting into the air from hole boring for the perimeter well-point system. Excavations for the cyclotron and experimental halls were completed in June, by which time 60,000 cubic metres of glacial till had been removed to leave a 120 m by 30 m by 13 m deep hole.

Several major contracts were also let over this period. Davie Shipbuilding in Québec won for the cyclotron magnet fabrication ($1.94 million), for which Stelco ($0.4 million) and Lukens Steel ($0.6 million) were to provide the steel plate — overall 75% Canadian content. Commonwealth Construction were awarded a $2.2 million contract for the concrete substructure — but were then delayed nearly three months by a construction strike/lockout.

The Central Region Model (CRM) — a 2.5 MeV cyclotron with the same magnetic and RF fields, 300 kV ion source, and injection line as the big machine — was taking shape in the office building. The huge vacuum tank (2 m wide by 10 m long) built by EbCo Industries arrived in April and was quickly pumped down to the required 5×10^{-7} Torr. The resonator panels, also built by EbCo, arrived soon after.

1971: CYCLOTRON BUILDING COMPLETE AND THE FIRST H- ION BEAM

In the year up to June 1971, construction of the main cyclotron building was the most visible progress at TRIUMF. The previous summer's enormous hole in the ground had been filled — first with a forest of rebar, then 25,500 cubic yards of concrete. Finally, the walls were crowned with the steel superstructure and roof, and the two 50-ton cranes were installed by June.

More major equipment and building contracts were awarded, with around 90% of the 1,970 contracts going to Canadian companies. Notably, TRIUMF's first Ph.D. was awarded to Robin Louis by UBC for his beam dynamics studies of the cyclotron's central region.

As well, the design vacuum of 3×10^{-7} Torr had been reached in the CRM, and the RF Group achieved their goal of 100 kV on the resonators in February 1971. Following this the magnet was installed and field measurements begun. The H^- ion source had arrived from the Cyclotron Corporation in October and was soon producing a 2.3 mA beam — the first particle beam at TRIUMF. The source was then tested at 300 kV and construction of the injection line started.

1971-72: CYCLOTRON CONSTRUCTION BEGINS

With the cyclotron building complete, assembling the cyclotron magnet and vacuum tank was the main activity from mid-1971 to mid-1972. The first of the six magnet sectors arrived in July 1971 from Davie Shipbuilding in Quebec. By January all had arrived and the lower sectors had been installed in the vault, allowing the entire staff to pose for an iconic photo (see Fig. 3).

Meanwhile, Ebco was busy in the Meson Hall assembling the gigantic (15 m diameter) stainless-steel vacuum tank, with its myriad field-adjustment and water-cooling coils. Tests showed that there were no leaks, and a vacuum of 2×10^{-7} Torr was achieved on the first pump down — a real tribute to the welders' skill. In February the tank and lid were lifted over the vault wall and lowered onto the lower magnet sectors, allowing the upper sectors to be installed in March. The 664 tie rods (supporting the 2660 tonne atmospheric load on the tank) were also installed, followed in April by the massive spider-web support structure.

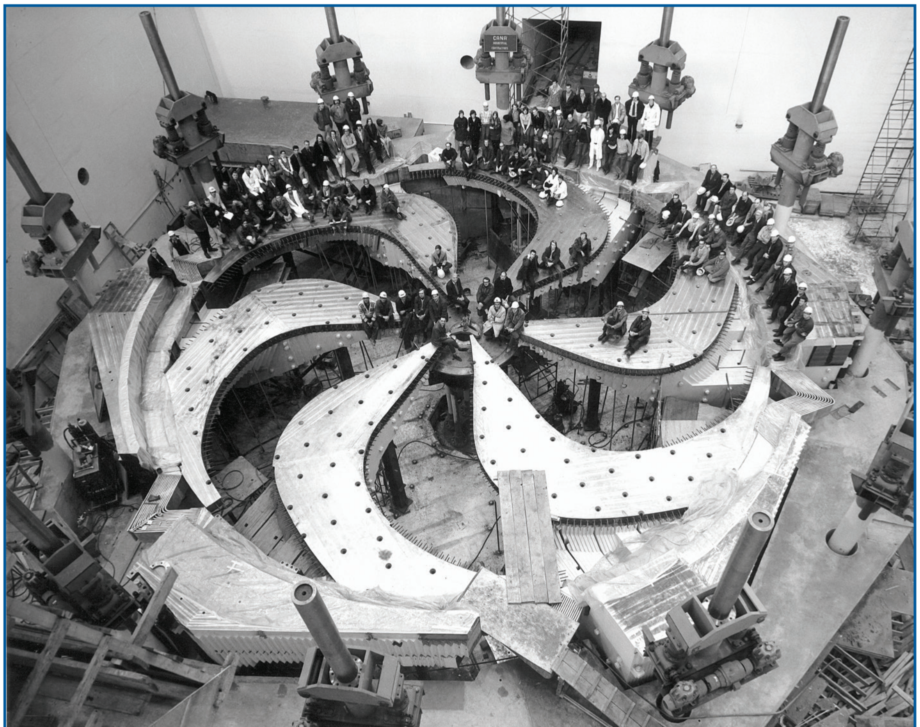

Fig. 3 The TRIUMF staff posing proudly in 1971 on the completed lower magnet sectors of the cyclotron.

RF tests on the CRM led to improvements of the resonator design, the fine-tuning mechanism, and the amplifier's control circuitry. Optimization of the injection gap required redesign of the spiral inflector, a prototype of which was then manufactured using UBC's novel computer-controlled milling machine and successfully tested to full voltage in vacuum. These efforts were crowned by the first successful beam injection into the CRM on May 12th.

John Warren completed his term as Director in September 1971 and was succeeded by Reg Richardson. September saw the first meeting of the Experiments Evaluation Committee, where 29 proposals were considered, an enthusiastic initial response by the user community that augured well for the future!

1972-74: TWO DIFFICULT YEARS

May 1972 until April 1974 was a period of great difficulties and delays, beginning with a 3 month-long general labour dispute in BC that delayed completion of the main cyclotron's magnet — the jacking system could not be finished until July 1972 and the six sectors of each magnet coil could not be welded together until August. Afterward, the 27,000 amp magnet power supply was commissioned and by mid-December the survey arm had been installed and ready to take magnetic field strength data inside the cyclotron (see Fig. 4).

But the first results were alarming! The mean field strength was 3% too high over the inner region and 3% too low at the outside, far outside the ~±0.01% design tolerances! Although the 1/10 scale model was built of plates from the same steel melt as the full-scale magnet, the rolling process had affected the surface magnetic properties, lowering the overall permeability more for thin plates than for thick ones. Moreover, in January the isolating transformer was destroyed by fire, delaying further measurements by three months.

Drastic surgery was required on the main cyclotron magnet. Over the spring and summer, 100 tons of steel were added to the outer return yokes and 16 tons cut away from the inner ones. This brought the field error down to ±0.1%, close enough to achieve the desired accuracy using just pole shims. As well, the magnetic field's azimuthal variation had to be adjusted to ensure vertical focusing and to eliminate harmonics, and any field asymmetry between the upper and lower magnets removed. In all there were 15 parameters to be corrected at each of 103 radii by adding or removing shims at up to 666 locations — a massive undertaking. Computer programs were devised to calculate the shim changes required, but the physical changes had to be made by hand.

In that era, codes demanded hours of dedicated overnight running on UBC's IBM360 mainframe. During the day teams laboured to implement the changes — very many iterations were needed, as crosstalk between the field parameters meant that improvement was slow. It took from September until April and the volunteer efforts of nearly everyone on site before the magnetic field was deemed accurate enough to commission the beam with trim coils alone.

Meanwhile the CRM was making good progress. The measured orbits agreed with computations and by October 1972 the beam reached the full 3 MeV energy while confirming its sensitivity to RF cavity misalignment and magnetic field asymmetries across the large pole gap. But with central correction electrodes, steel shims, and trim coils, the beam could be brought sufficiently close to the mid-plane, and by June 1973 the design 100 μA beam intensity had been achieved.

1974: CYCLOTRON COMPLETED AND BROUGHT TO LIFE!

With the Herculean task of reshaping the cyclotron magnet completed in April 1974, the lab's efforts shifted to installing the equipment needed to inject, accelerate and extract the beam.

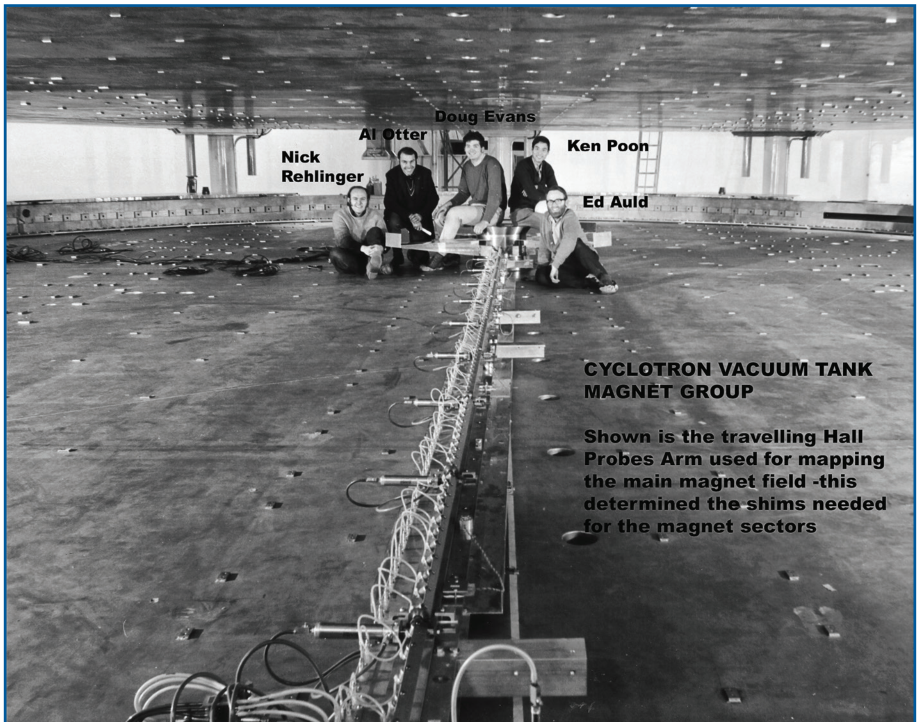

Fig. 4 The magnet survey group circa 1973, led by UBC Professor Ed Auld, inside the cyclotron tank.

First, the vacuum tank was carefully aligned (by adjusting some 500 tie rods) and turned into a clean area. 80 RF resonator sections (each about 5 m × 0.8 m) that had already been carefully assembled, washed, baked, and leak tested were installed, followed by seven weeks on a 14 shift/week schedule to align them! Electrical tests started with connection of the 30 cm-diameter transmission line from the 2 MW RF amplifier to the coupling loop. The resonator Q value was found to be 6400, very close to that expected. Resonator vibrations induced by the cooling water were damped by a combination of mechanical dampers at the tips and "Chore Girl"-brand copper-mesh kitchen cleaners under the header lines.

Meanwhile, the turbo pumps, sublimation pumps, and 20K cryopanels were installed, and by early September a tank vacuum of 5×10^{-7} Torr was achieved. But RF power tests led to unacceptable hydrogen outgassing, so the sublimation pumps, with their low capacity for hydrogen, were replaced by oil diffusion pumps. This allowed 50 kV RF operation and eventually 90 kV by October, sufficient to accelerate H^- beam around the centre post.

As a 100 μA H^- beam had already been achieved in April through the injection line's horizontal section, the summer was devoted to installing and commissioning the vertical section. This was followed in October by installing the spiral inflector, allowing injection of a 6 μA H^- beam into the cyclotron. By this time at least one each of the centring, low-energy, and high-energy beam probes were in place and operational, along with a variety of correction plates and collimating devices in the central region and the extraction foil for Beam Line 4. Outside the cyclotron a host of activities crucial to its successful operation were under way: developing an effective control system, building an external beam line, providing electrical services and water cooling, laying cables, and so on.

By November 16th all was ready for the task of coaxing the H^- beam through the cyclotron by fine adjustments to the magnetic field — a daunting proposition due to the large number of orbits, high RF harmonics, weak vertical focusing, and a large pole gap. Fortunately, the Director himself, Reg Richardson, was a champion cyclotron tuner — dubbed a "ten-knob man" at Berkeley for his dexterity at the controls. His office armchair was moved into the Control Room, where he installed himself to manually adjust the 54 circular trim coils and 78 harmonic coils.

On that first day, good progress was made through the tricky first turns, and two days later the beam had been guided to a 2 m-radius orbit at an energy of 22 MeV, with the excited entry in the logbook, "Radiation in vault!!". Steady progress was made and in spite of losing 7 days to breakdowns, 295 MeV was reached by December 1st. But the orbits crowd closer together at high energies, making tuning very difficult, and 6 days were lost to breakdown of the ISIS 300 kV power supply, so that by December 14th we were still only at 363 MeV.

Fig. 5 TRIUMF Director Reg Richardson (seated) at the controls when the first beam was extracted from the cyclotron December 15, 1974. The author (Mike Craddock) is seen directly behind Richardson in the black shirt and vest.

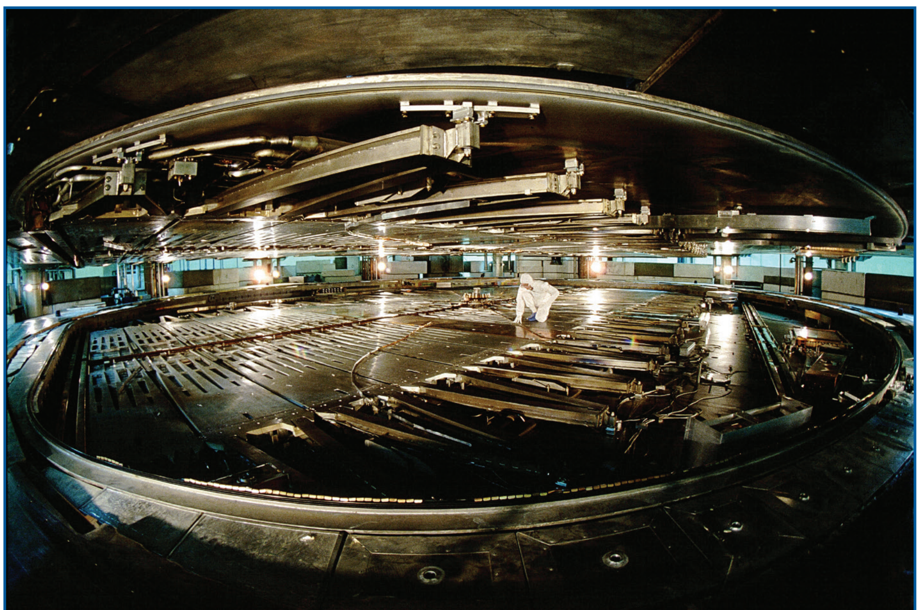

Fig. 6 Inside view of the completed TRIUMF cyclotron.

However, the next day it took Reg only an hour to bring the ions to the long-awaited goal of 500 MeV. Beam line 4V magnets were then turned on and when the H^- ions were allowed to hit a stripper foil, protons were immediately detected in the vault. It then took just over an hour to steer and focus the beam to a 1 cm-diameter spot on a scintillator screen — a great demonstration of the simplicity of extraction by stripping (see Fig. 5).

It would be hard to exaggerate the relief and exhilaration everyone felt at having finally achieved the goal we had worked towards for so many years. The news spread like wildfire and the Control Room was soon inundated with visitors from both inside and outside the lab, many of them bringing refreshments for an impromptu celebration.

For the TRIUMF users of course this was just the beginning, their challenge was to put this powerful tool (see Fig. 6) to effective use, as it was the staff's challenge to develop the facility's full potential. Happily, over 40 years of highly productive research in a wide variety of fields show how well both groups have succeeded.

Article has been edited for brevity by Marcello Pavan.