# TRIUMF

# ANNUAL REPORT
# SCIENTIFIC ACTIVITIES
## 1998

CANADA'S NATIONAL MESON FACILITY
OPERATED AS A JOINT VENTURE BY:

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

APRIL 1999

*The contributions on individual experiments in this report are outlines intended to demonstrate the extent of scientific activity at TRIUMF during the past year. The outlines are not publications and often contain preliminary results not intended, or not yet ready, for publication. Material from these reports should not be reproduced or quoted without permission from the authors.*

# ISAC PROJECT

## INTRODUCTION

TRIUMF has again this year heavily invested resources into the ISAC project. The results and milestones, described in the following pages, are evidence that the investment has provided many observable successes. In fact, a major milestone, namely the achievement of radioactive ion beam to the low energy experimental area, was achieved approximately one month ahead of schedule. This milestone required a completed BL2A, a full set of target modules, completed radiation shielding and safety system, mass separation system, low energy beam transport to TRINAT, controls, TRINAT and an AECB operating licence. Although this part of the project received priority, progress continued with the accelerators and beam lines required for the astrophysics program. The RFQ accelerated beam from the off-line ion source up to 54 keV/amu, displaying an acceptance similar to that projected.

The first ring buncher required by the DTL was tested successfully at full power. At year end the first tank of the DTL was ready for power tests. Many of the magnetic components required for the MEBT and HEBT were acquired from the TASCC facility. Consequently, it appears that ISAC should be able to begin the high energy physics program by the end of 2000. In anticipation of the next five year plan, a concept design has been prepared which would allow the beams to be taken up to 6.5 MeV/amu for masses as high as 150.

## SCHEDULE AND PLANNING

The Planning group was actively involved in planning, scheduling, coordinating and expediting several sub-projects for ISAC. Various plans and PERTs were prepared, manpower estimated and analyzed and PERTs were updated regularly. Priorities were evaluated and the highest priority was assigned to produce the first radioactive ion beam (RIB) from ISAC by the end of November. This required the completion of beam line 2A, target areas with five modules and shielding, separator system (pre-separator, mass separator and LEBT to TRINAT). The resource levelling was done, activities were expedited and this goal was achieved on schedule with the first RIB with ISAC on November 30 and RIB delivered to TRINAT on December 5. Other intermediate milestones which were planned and achieved in 1998 include:

- February: 11 MHz, saw-tooth buncher test;
- April 29: proton beam to temporary dump;
- May 25: proton beam to the dump module at west target station;
- June 6: first accelerator beam out of RFQ with $^{14}$N;
- July 13: full voltage on RFQ electrodes;
- September 24: first stable beam out of exit module at Faraday cup;
- September: accelerated beam out of RFQ at full power;
- October 23: first stable beam through pre-separator;
- October: DTL rebuncher tested to full power;
- November 3: first high resolution beam at separator image slit.

Approximately 89% of the total available Design Office effort and 83% of the total available Machine Shop effort were invested in ISAC. In addition, significant design and assembly support was provided by the University of Victoria and other groups at TRIUMF (Beam Lines, RF, Targets) to meet various challenging schedules. The PERTs of ISAC sub-projects which required substantial manpower from various groups included: completion of beam line 2A; target hall (target stations, five modules, shielding and remote handling); separator system (pre-separator, mass separator plus LEBT with associated diagnostics, controls and services); RFQ task force (off-line source, LEBT, RFQ with seven rings plus optics and diagnostics), TRINAT (move from proton hall to ISAC and new LEBT), GPS (tape drive system and LEBT), DTL (tank 1 and rebuncher); and MEBT (prototype buncher).

Progress on PERTed projects is described elsewhere in this report under the respective principal group. The following is a summary of projects along with major milestones planned and achieved, which required a substantial part of the Planning group's effort in planning, scheduling and expediting various activities.

### Beam Line 2A

Major emphasis was to complete the installation and commissioning of the vault and tunnel sections. Beam line 2A was commissioned with proton beam to a temporary dump (in the tunnel) on April 29, and to the dump module at the west target station on May 25.

### Target Areas

Work primarily included fabrication, assembly, installation and alignment of 2 vacuum tanks; fabrication and assembly of 5 target modules for the west target station (entrance, dump, target and 2 exit modules); target hall crane; guard rails, walkways and refinishing of target hall concrete walls by surface parging and painting; shielding (up to 525 tons of concrete poured in several steps and 1,000 tons of steel shielding); high voltage system (cage, interlocks and HV lines); services (electrical, water, air); vacuum system; target station (module access area, services, cabling); machine protect system (interlocks, thermocouples, etc.).

Several problems were encountered in the fabrication and assembly of two vacuum tanks and many target module components due to poor copper plating, design and manufacturing errors compounded by the lack of quality control and proper timely inspections of fabricated components. Consequently, more manpower was required to correct technical problems and the milestone of extracting stable beam out of the exit module at the Faraday cup was achieved approximately two months later on September 24.

### RFQ

Along with installation and alignment of the platens, seven rings and rf shroud in an 8 m long RFQ tank; the rf short, LEBT from OLIS to RFQ, optics and diagnostics were also installed with the associated vacuum system, services and controls to test RFQ with seven rings up to 60 keV/u. After systematic bead pull measurements and rf tests (signal and power level), full voltage on RFQ electrodes was achieved on July 13. First accelerated beam with $^{14}$N was extracted through the RFQ in June and with $^{28}$N at full power in September. More beam tests will continue until January, 1999. All 19 rings were designed, fabricated and assembled by December, with an aim to send out for EDM in February, 1999, completion of installation of all rings by July, 1999 and signal level and power level rf tests by October, 1999.

### Separator System

The pre-separator was received and field mapped in June and installed by September. A maze to separate the pre-separator section and the mass separator pit was designed and built during the summer. The mass separator, high voltage platform, diagnostics, vacuum system, controls and LEBT (from DB11 to TRINAT) were installed and tested by October. The commissioning sequence involved getting the first stable beam through the pre-separator on October 23, the first high resolution beam at the separator image slit on November 3, followed by a stable beam to TRINAT on November 19, and RIB with ISAC on November 30.

### Drift Tube Linac (DTL)

The overall progress on the DTL project was slow due to a relatively higher priority (in terms of manpower and other resources) placed on getting the RIB to TRINAT by the end of November.

After prototyping and a few design iterations, the first tank (including stems, ridges and end plates) was fabricated and copper plated by September. However, due to problems associated with copper plating of the tank and DTL components, the installation and alignment were delayed until January, 1999 and will be followed by rf tests by May, 1999. The DTL buncher was designed and fabricated at INR, Troitsk. It was received at TRIUMF in August and tested to full voltage by October. The plan is to order the other two bunchers (after evaluating the tests) by February, 1999. The DTL triplet was specified and design was started. It needs higher priority so that it can be reviewed and ordered by April, 1999 or earlier, and then field mapped and installed by November, 1999.

### DRAGON

A work breakdown structure (WBS) was developed and a detailed PERT was prepared and updated regularly. The progress and major milestones included: gas target designed and fabricated at the University of Alberta with an aim to test at TRIUMF in May, 1999; two magnetic dipoles (MD1, MD2) designed and will be ordered in January, 1999; design of two electrostatic dipoles (including electrodes, HV power supplies, support and alignment structure) started.

### Manpower

Manpower estimates for all ISAC sub-projects were completed showing heavy manpower requirements in 1998 and 1999. Priorities were evaluated and work on the DTL and RFQ 19 rings was given a lower priority compared to activities required to produce the first RIB to ISAC by the end of November.

In addition to the above sub-projects, the Planning group was actively involved in planning, scheduling and expediting the activities for the GPS experiment, the TRINAT move to the ISAC building, LEBT (to TRINAT and GPS), yield station, MEBT layout, LNTO (for beam in July, 1999) and $\beta$-NMR (for beam in November, 1999).

## CONTRACT ADMINISTRATION

In the past year, five contracts were awarded. Holaco Construction Ltd. (B.C.) built miscellaneous concrete shielding blocks for the target hall. Sunrise Engineering Ltd. (B.C.) was awarded two contracts; the pre-separator magnet and the first drift tube linac tank

DTL1. Talvan Machine Shop (B.C.) built the 45 degree dipole magnets for the MEBT. The coils were sub-contracted by Talvan to Stangenese Industries Inc. of California. Brandt Industries Ltd. of Saskatchewan built nine target station shield plugs which were used to cover the module shield plugs in the target tanks.

**Personnel Resources**

In 1998 the personnel effort for ISAC increased steadily to average 79.97 full time equivalent (FTE) people per month, compared to an average 63.6 FTE people per month for 1997 and 39.6 FTE people per month in 1996 (see Fig. 118).

In 1998 the average personnel effort per system (see Fig. 119) was as follows:

Table XIX. Personnel effort per system.

| System | Monthly FTE |
|---|---|
| Project management & administration | 4.06 |
| Beam line 2A | 6.55 |
| Target station | 12.13 |
| LEBT | 9.69 |
| Accelerator | 13.22 |
| Science facilities (TRIUMF personnel) | 10.06 |
| Infrastructure | 9.33 |
| Integration | 12.95 |
| Science facilities (non-TRIUMF personnel) | 1.98 |
| Total ave. FTE monthly personnel | 79.97 |

The total personnel effort since the project began is shown in Fig. 120. The graph illustrates the total FTE years per project section. The combined effort totals 183.62 years of work, based on a FTE month of 150 hours.

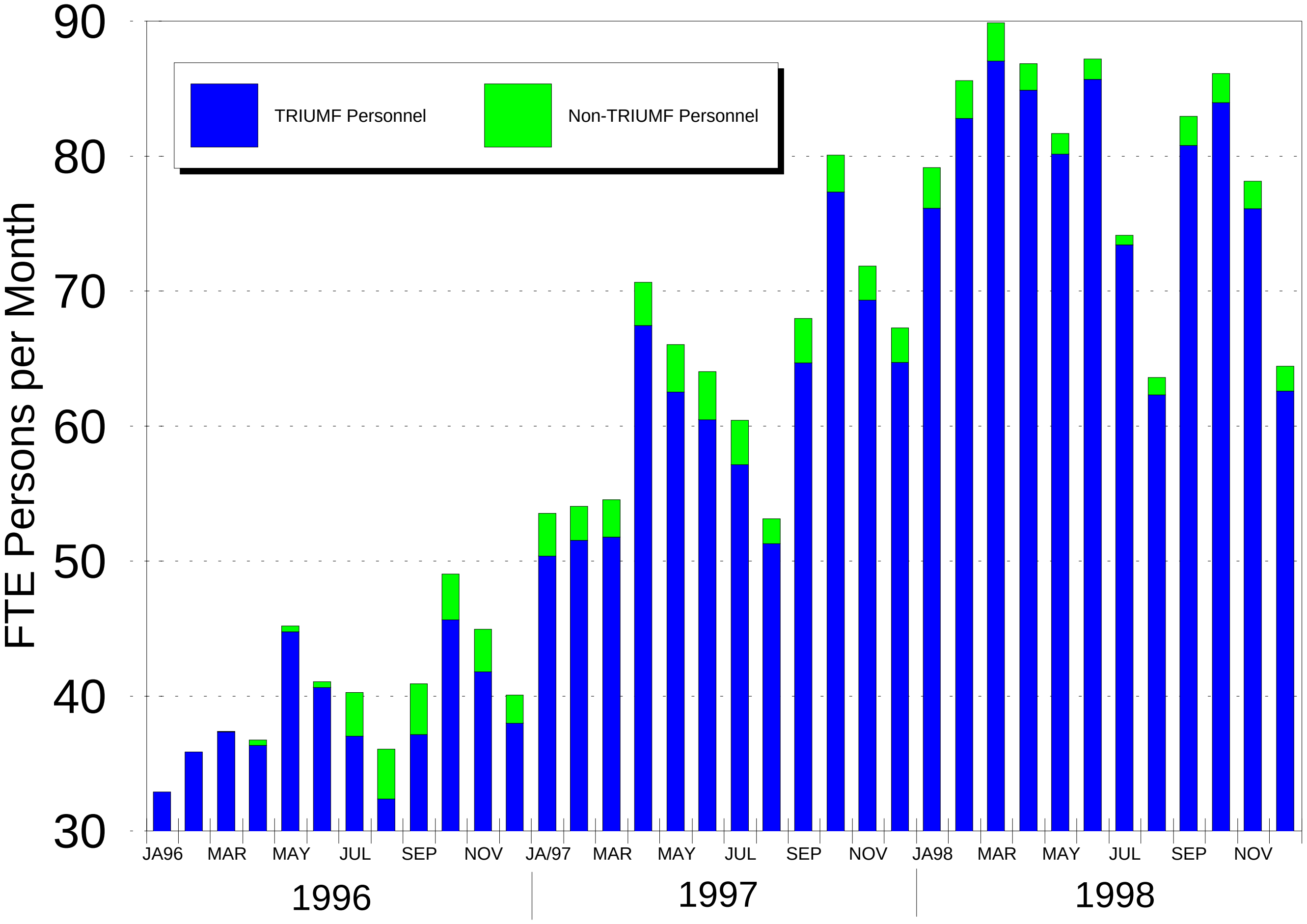


Fig. 118. ISAC project personnel, January 1, 1996 to December 31, 1998.

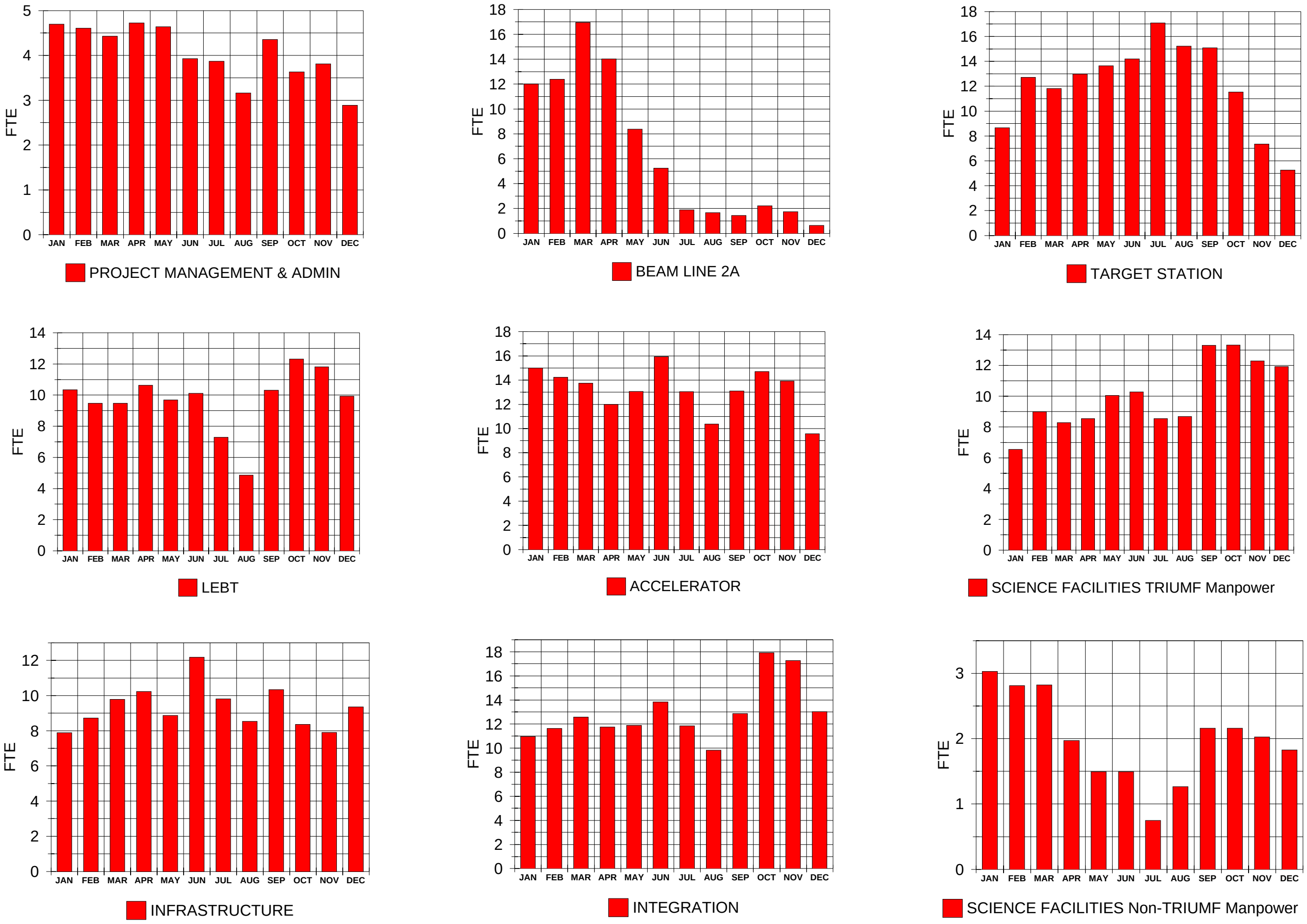


Fig. 119. ISAC personnel. Monthly FTE people for 1998 (by system).

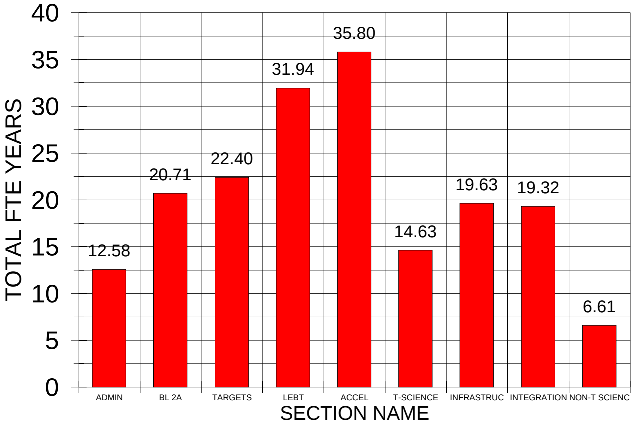


Fig. 120. ISAC project personnel, January 1, 1996 to December 31, 1998.

## CONVENTIONAL FACILITIES AND INFRASTRUCTURES

1998 was the year in which the formal occupancy of the ISAC building was obtained. Two of the major contracts remaining, namely electrical and mechanical, were formally completed early this year. With their completion the UMA group project management team reduced its presence and left the site in February. TRIUMF ISAC technical facilities assumed direct responsibility for the completion of the conventional facilities while UMA helped manage the transition. Many other contracts were brought to completion during the year, including the upgrade to the fire alarm system to satisfy the new requirements of the fire department. We also supervised the warranty repair work carried out by various contractors. The extra claims by Swagger Construction Ltd. were successfully settled during the summer with mutual satisfaction. NORELCO continued to work at solving the target hall crane radio controls problems. After many ideas were tested in the field with partial success it was decided to re-engineer the whole controller design. The upgrade will be commissioned in 1999. The last phase of the target hall shielding was installed in the spring along with a masonry block maze to the pre-separator. After concerns were raised that potential radiation contamination may accumulate in the large holes in the walls, the target hall walls were surface parged and painted. The construction of the TRINAT clean room was completed in the summer along with the preparation of the area to house the LEBT vertical section. Covers for the experimental hall mezzanine were gradually installed during the fall. Once the major construction activities were completed a systematic cleaning program was started in the fall to make the ISAC facility a fully operational laboratory. Continuing support was provided to the Science Division for development of the arrangement of the experimental facilities and integration with the rest of the accelerator systems and building services. In the late summer we finally managed to re-do the landscaping of the boulevard along the road to TRIUMF.

### Data and Ethernet Communication

The data communication system for ISAC was a major project this year. All conduit were traced, confirmed and mapped to AutoCAD drawings after it was discovered that the contractor as-built drawings were not accurate. February to June were dedicated to pulling twisted 100 base-T cables, making terminations, jumpers and commissioning. TRIUMF personnel pulled the fibre optics cables, but the terminations and testing were contracted out. During the remainder of the year we continued to add to the system as required for the ISAC controls and TRINAT. Some of this work involved installing fibre optics isolated systems due to the special grounding requirements of the target systems and the mass separator. In November ISAC was formally connected to the rest of the TRIUMF site and the Internet. Altogether 124 twisted cables and 3 sections of fibre optics cables ranging from 200 ft to 550 ft were installed. There are 212 data connections available, with a fibre optics backbone that connects to the rest of the site network and the Internet.

### Electrical Services

Another extremely busy year was dedicated to the design and installation of the services to the systems required for the first ISAC experiment in the TRINAT experimental set-up. Since TRIUMF was not staffed to carry the workload with its internal resources, an arrangement with outside contractors was made to retain flexibility during construction while keeping costs under control. TRIUMF supplied all design and engineering, procured all material, and coordinated the work of the outside labour force. The task was particularly challenging but in the end proved to be successful. The arrangement allowed the necessary flexibility to proceed with the installation of services to systems that were not fully specified in detail and to retain control of the installation of especially critical systems like the mass separator grounding. A good example of the above is given by the pre-separator services and controls relocated to the electrical room after the decision to move the TRINAT lab in the mass separator support room.

Major tasks completed during the year included the installation of cable tray systems and ac power services for the following systems/areas:

- Beam line 2A tunnel side and associated auxiliaries
- Electrical room and target ion source Faraday cage
- Target hall and west target station and associated cooling and vacuum packages
- Mass separator, pre-separator, and low energy beam transport to the experimental hall
- TRINAT clean room
- GPS and LEBT in the experimental hall
- RFQ and auxiliaries, including vacuum pumps, cooling systems and bake-out, and controls for the blanket electrical heaters
- Extensive conduit runs for the radiation safety monitoring systems and area safety units
- Mass separator isolated grounding.

The commissioning of the RFQ amplifier revealed that the specified tripping speed of the line breaker was not adequate to protect the rf tube in case of an internal short circuit. To reduce the breaker tripping speed from 55 ms to 20 ms required the coordinated effort of the supplier as well as TRIUMF engineers and a series of tests to determine the optimum voltage to apply to the tripping coil.

The rf grounding was engineered to force the return of rf leakage currents back to the source through the rf transmission line. All the remainder of the structures were isolated except for a safety ground wire which offered a high impedance path to the rf signal.

The design of the grounding system for the target ion source–target station–pre-separator–mass separator systems required a particular effort. This grounding must provide a voltage stability of ±1 V/60,000 V between the ion source terminal room and the exit slit of the mass separator located about 60 linear feet away for power frequencies up to the 50 harmonics (3,000 Hz) in order to provide the required signal reference stability to achieve the desired mass resolution in the spectrometer. The initial design of a single-point signal ground plane embedded in the concrete floor had to be changed once it was found out that the large surface available around the target station and the limited electrical resistance (k$\Omega$) offered by the concrete would prevent maintaining a good ground isolation all the way from the ion source to the mass separator exit slit. The new design incorporated a signal ground plane made of a 12 in. copper strip, completely isolated from the building structures and the target station frame, run from the ion source terminal room ground plane to the mass separator ground plane. The ion source itself was isolated from the rest of the target module metal frame and connected back to the terminal room via isolated ground wire. The grounding of the two ac power distributions to the ion source terminal room and the mass separator beam line had to be engineered to accommodate the above requirements. The installation of the public address system was postponed to the next fiscal year and the required manpower was busy in other priority tasks. The OLIS safety interlocks were completed and the system declared fully commissioned. Some rf noise problems emanating from the source were addressed and corrected.

### Mechanical Services

The ISAC activity may be divided into two classifications: the contractual project and the post-contractual projects. The contractual project was carried out under the management of UMA Projects, the project manager for the construction of the conventional facilities. The post-contractual projects were managed by TRIUMF and included the connection of the beam lines, targetry and experimental facilities to the backbone systems built under the contractual project.

The contractual project saw the completion of the construction, the start-up and commissioning of the building mechanical systems. This work was managed by UMA Projects with the coordination of TRIUMF and the supervision of Keen Engineering, the mechanical consultant responsible for the design. The installation was carried out by the main contractor, Lockerbie and Hole, the controls were by the subcontractor, Modern Systems Management, while KD Engineering performed the commissioning of the water, compressed air, ventilation and sump systems. Wherever possible, systems were 100% complete, for example: building HVAC, washroom facilities, storm drainage. However, some systems were left in a “roughed-in” condition for completion in a post-contractual project as beam lines, target modules and experimental systems were completed. Examples of these are the cooling water distribution to beam line components and the radiation exhaust ducting into target areas. Work on the contractual project was essentially complete by spring.

The post-contractual projects occupied the majority of effort in 1998 and covered all phases from design, procurement, contracted installation supervision, and commissioning. A series of milestones was reached on time and under budget. These projects can be classified as supply of cooling water, compressed air and vacuum pumps exhaust connection to the radiation exhaust system, and air handling systems.

Air, cooling and vacuum exhaust installations completed during the year in rough order of magnitude included:

- the high active low conductivity water cooling system (HALCW) for the target stations and services in the target hall,
- the RFQ and associated PA-dummy load bakeout systems,
- plumbing for the mass separator–pre-separator–maze–LEBT, TRINAT clean room, electrical room and target ion source terminal room in non-conductive material,
- 2A vault and 2A tunnel beam lines and relative power supplies,
- LTNO and GPS services,
- nitrogen capping and resistivity sensors for the low active and non-active LCW systems.

The air handling and ventilation jobs included:

- the TRINAT clean room air conditioning;
- the extension of the radiation exhaust system to the target area;
- HVAC extension into the Faraday room with grounding isolation;
- the installation of HEPA filters and monitoring instrumentation into the target area, mass separator area, 2A tunnel and mechanical penthouse;
- the connection of the TSG monitoring system exhaust to the radiation exhaust system.

In addition, the experimental hall crane north-south drive controls were revised to obtain a finer motion control.

### Voice and Telephone Communication

Telephone services were initially provided with temporary cabling as installation and commissioning personnel moved into new areas of the building during the ongoing beam line construction stage. Permanent cabling was completed by BC Tel in early May. Telephone installation and programming were carried out by the TRIUMF telephone group and to date 28 locals serve a large portion of the ISAC facility. The ISAC telephone system is fully integrated with the rest of the TRIUMF system. The TRIUMF system has a limited capacity for additional locals to ISAC. The telephone management group is reviewing the situation to determine whether to expand the existing hardware or recover locals from elsewhere on site.

## ISAC-I EXPERIMENTAL FACILITIES

Having defined the initial ISAC scientific program with the help of the ISAC Scientific Advisory Panel, users met biweekly during the year to organize the experimental hall and define the required experimental facilities. The experimental space available has been subdivided between a low energy area where beams of up to 60 keV produced from ISAC are used and a high energy area which will make use of the accelerated beams (up to 1.5 MeV/amu) in the year 2000.

Figure 121 gives the current agreed upon layout for the beam delivery system. One experimental area is not shown on this diagram because it is occupying the mezzanine directly above the separator room. Because of the shielding and strict environmental requirements, the TRIUMF neutral atom trap has been located on the mezzanine. It is described on page 45 of this Annual Report.

The low energy area is shared between two main beam lines; one feeds the general purpose tape station (see Expt. 823, page 60), and the low temperature nuclear orientation set-up (see LTNO, page 118). It will accommodate other stations along the main backbone beam line in the future. The second beam line will feed initially a polarizer section to produce polarized ion beams for a condensed matter program. The first such beam will be $^{8}$Li which is being developed on the ISAC test stand (see page 154). This same beam line will have a Paul trap to bunch the ions which could feed a Penning trap system as well.

In the high energy area, two beam lines are anticipated initially: one feeding the DRAGON recoil spectrometer system (see DRAGON report, page 119), the other a general purpose scattering facility to be developed in collaboration with the University of Edinburgh. During the past year, considerable engineering studies helped freeze the final configuration for DRAGON which occupies a large piece of real estate in the hall.

As reported in this document, two experimental stations, TRINAT and GPS, were commissioned in time to accept the very first potassium beams from ISAC. The LTNO fridge was moved from Oak Ridge and is being recommissioned in the ISAC hall. Designs of the $^{8}$Li beam system and of a $\beta$-NMR spectrometer were finalized. Designs of the DRAGON spectrometer elements were also finalized, and tendering and procurement are being carried out.

The successes of the ISAC construction teams are now coming to the attention of the physics community and new groups are considering moving some of their experimental programs to ISAC.

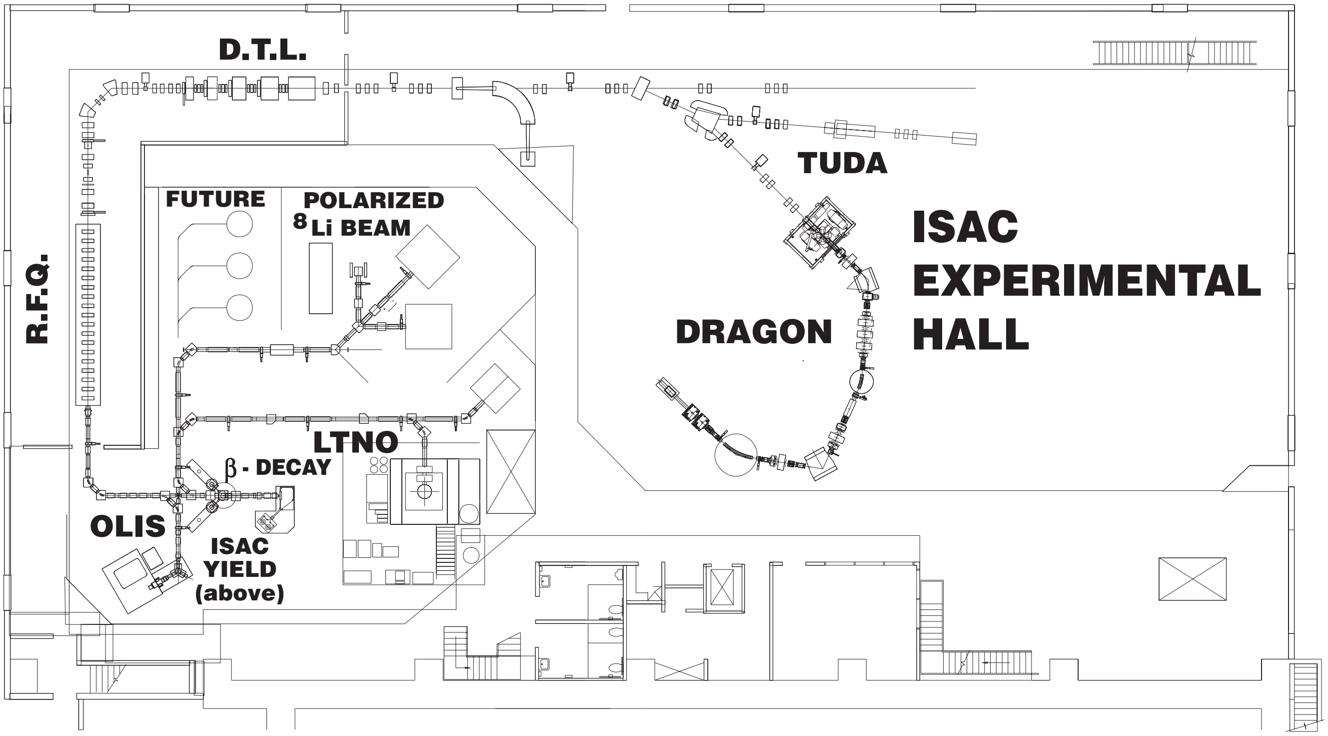


Fig. 121. ISAC experimental facilities and beam delivery systems.

## TARGET HALL

The function of this hall (from west to east) is to contain two target stations and most services, a storage pit, two hot cells, an entry hatch and several landing areas. The hall itself acts as a radiation shield during operation and target module transport to the hot cells. The hall is 137 ft long (E-W), 18 ft wide and 45 ft high, with the lowest level at 264 ft at the bottom of the storage pit. The entire area is serviced by a special 20 ton crane which ultimately will be remotely controlled from the remote handling control room.

At the end of 1997 work had just begun to construct the two target stations and the service zone at the west end of the hall. This was the major undertaking of 1998 and involved seven steps requiring framing and concrete pours, several steps requiring 10 ton steel block placements as well as electrical and ventilation chases and numerous service ducts, conduits and penetrations. This work had to be done accurately to satisfy the requirements of the placement of the two target tanks and minimize surrounding air gaps to reduce radiation activation. Many gaps were packed with scrap steel to augment shielding. The final result is a chevron-shaped pit that surrounds the two target vacuum tanks and the pre-separator magnet at its apex (see Fig. 122). The tanks sit on three alignment pins that are part of a prealigned alignment frame buried in the concrete. Construction was so precise that very little final adjustment was required. In the end, the seven steps involved 525 tons of concrete poured and 1000 tons of steel placed. Work then began to prepare the west target station – installing and aligning the vacuum tank, installing the high voltage conductors in the chase, installaton of services, etc. In September, the five modules were installed and aligned and stable beam was produced and transported to the Faraday cup in exit module 2 and through the pre-separator magnet shortly thereafter. Radioactive beam was produced in early November and transported to the yield station in the experimental hall later that month.

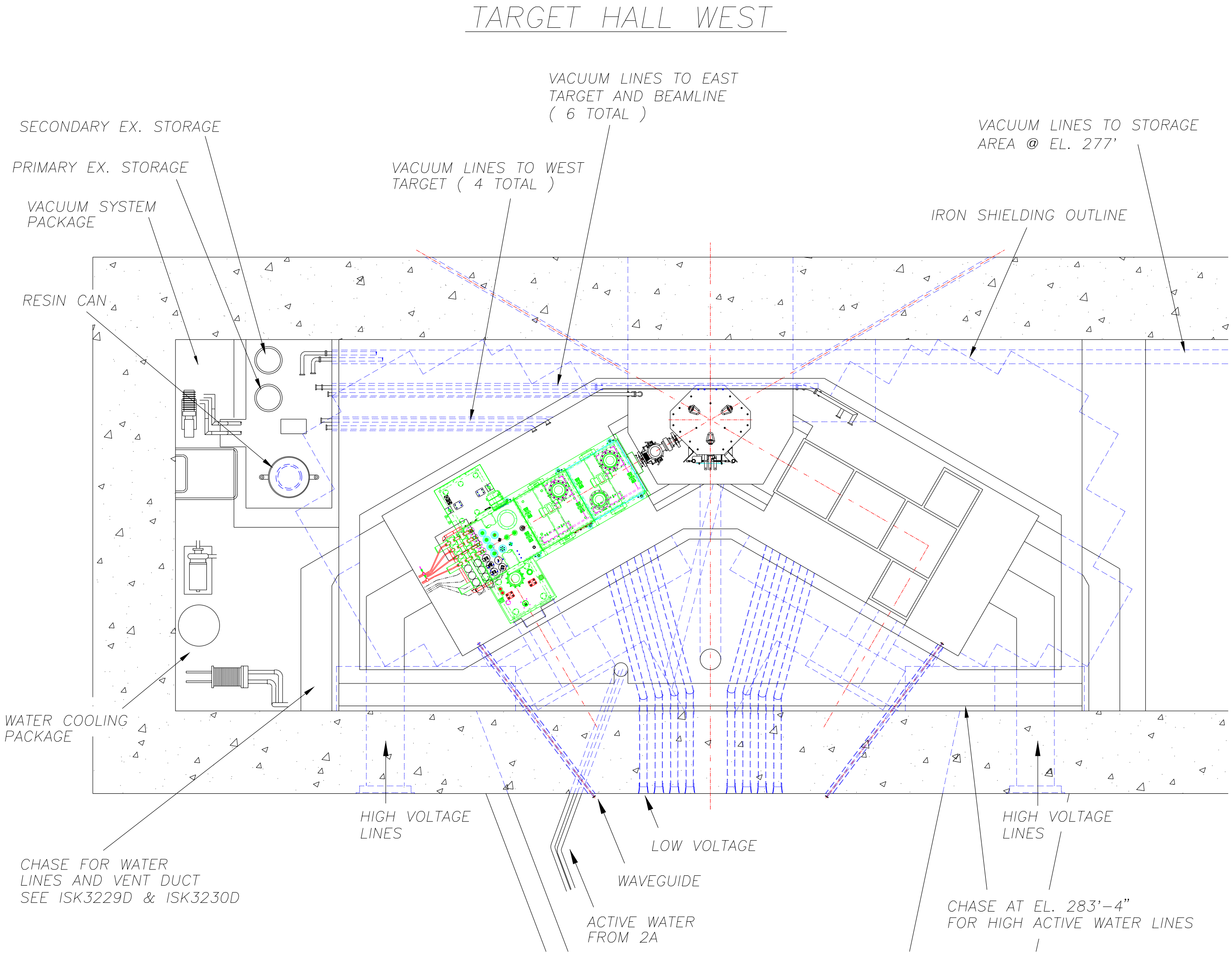


Fig. 122. Arrangement of target stations within the target hall.

Elsewhere in the target hall and in parallel with the aforementioned work, the crane was installed and, after many initial problems, was eventually commissioned. Some problems have persisted and are still being evaluated.

The storage pit was utilized as a work area once the module alignment frame was installed. Completion of the storage pit and hot cells will commence in 1999.

Other activities in the target hall involved the installation of walkways and guard rails, steps into the storage pit and a total refinishing of all concrete surfaces within the hall by surface parging and painting.

## Shielding

The target hall design stems from its primary function which is to shield adjacent work areas from radiation during operation and module transport. This has already been described in the previous section insofar as the target stations are concerned. The design concept is based on an extensive investigation into projected radiation levels in the adjacent work areas. The steel and concrete surrounding the target stations, combined with the 4 ft walls, ensure that radiation levels are below 10 $\mu$Sv/hr in these areas. To complete the picture, special removable, triangular shield blocks cover the pre-separator magnet leaving two rectangular volumes above both target stations. Each of these volumes is covered by five steel/concrete shield blocks that also are removable. Thus, the operating station is covered while the other station is not and radiation levels are such that workers can be at the non-operating station. All this special shielding required special form work and the introduction of steel pallets as the concrete was poured to achieve the optimum shielding protection. These blocks were manufactured as steel boxes off-site and filled at TRIUMF. The other specially shaped shield blocks were formed and poured on-site. All were built during the latter half of the year.

During 1999, more shield blocks will be produced to provide shielding in the service zone for the high active water package and the vacuum storage tanks. There will also be a requirement for special shielding in the storage pit and for shielded storage silos for modules.

## Target Station Modules

All five of the modules for the west target station were built, leak checked, aligned, installed and operated in 1998. The entrance module and dump module were completed first since they are smaller and simpler and the others followed until completion in early fall. Figure 123 shows the target module.

Assembly of the modules took place in the east end of the ISAC experimental hall where an assembly area was created. This involved the construction of a large U-shaped assembly frame to support all five of the modules during assembly (approximately 56 tons). There were several problems associated with the assembly, mainly due to manufacturing errors arising from the very tight schedule. For example, one unexpected problem was with the copper plating. All the shield plugs of the five modules are mild steel, copper-plated for corrosion protection. A large number of the pieces began to blister after delivery and had to be replated. This was a result of poor preparation prior to plating. There were also certain aspects of the design that were found to be impractical and required changes such as the containment box used at the bottom of the target and exit modules. The design was altered and the piece parts modified accordingly.

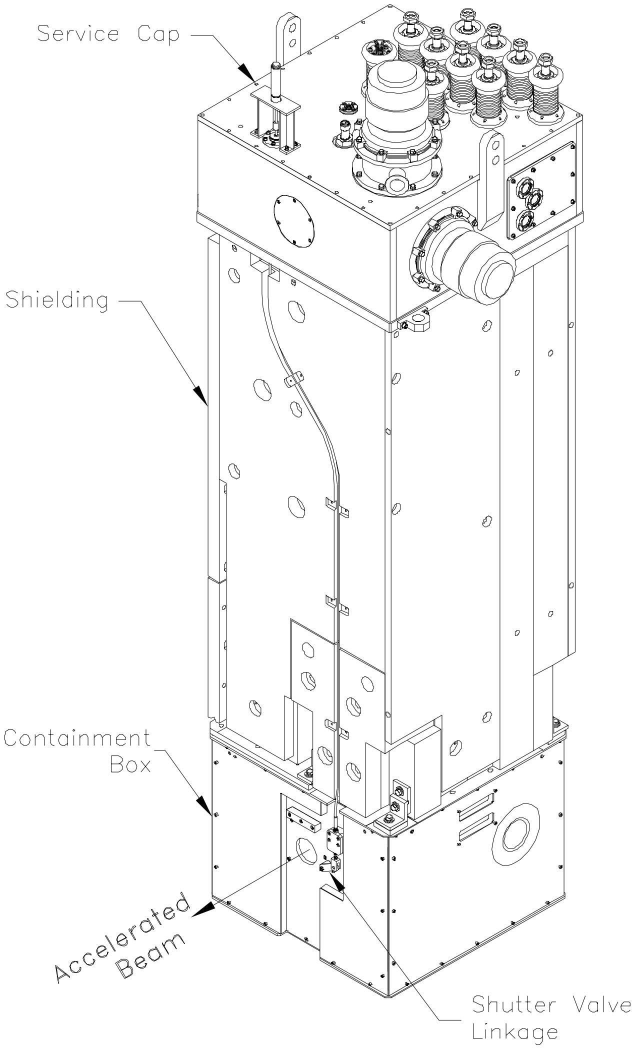


Fig. 123. Target station module.

Once the modules were in a semi-complete state they were placed in the east target vacuum tank (not yet installed) for leak checking. This proved to be a very tedious task due to the sheer number of welded joints and O-ring joints. Eventually this was overcome and after the tank was installed and aligned the modules were installed and installation of the services could then be completed. The target module required several iterations of modifications subsequent to this due to high voltage sparking in the service duct. This involved altering insulator supports and redesigning corners and adding smooth sheet metal at the entrance and exit of the duct.

Another very important step in the assembly of the modules was alignment. This is reported in the Remote Handling section of this Annual Report. Each individual component in the target and exit module containment boxes had to be aligned to each other and then aligned relative to the module alignment pins at the top flange. A series of jigs and fixtures were built to achieve this. Although very difficult to check once the modules are installed, there is confidence that errors are <0.010 in relative to true position.

The goal of all of this work was to achieve stable beam to TRIUMF in October and radioactive beam to TRIUMF in November. This goal was achieved.

### ISAC Diagnostics

The west target station entrance module diagnostics, associated drive mechanics and controls were built and installed in time for the 2A commissioning beam tests in May. The pneumatically driven retractable beam position monitor 2A2M19 design is based on the standard 32 by 32 multiwire monitor package with a two inch aperture. The design incorporates remote handling connectors and a replaceable monitor head. A multiwire monitor head was chosen to facilitate the beam commissioning and initial operation up to 1 $\mu$A; but as with the beam line 2A profile monitors a scanning wire head can be installed for use at higher beam currents. The last elements in the entrance module just upstream of the target are the stationary protect monitor and water cooled copper collimator. The protect monitor which is mounted directly to the collimator consists of a set of transverse aperture plates and a halo plate. To minimize scattering, there is no total current foil. The collimator and protect monitor present a 0.75 in. diameter aperture.

The exit module diagnostics and their associated drives and controls were designed, built and installed in time for beam commissioning in the fall. Exit module 1 contains a multiwire profile monitor ITW-harp3 and a three position collimator ITW-col3. Exit module 2 contains a multiwire profile monitor ITW-harp5A, a three position collimator ITW-col5 and a Faraday cup ITW-FC5. These are all pneumatically driven and designed with remote handling connections.

Multiwire monitor ITW-harp5B and the diagnostics stations IMS-DB0 and IMS-DB10A were built in the fall and installed in time for the stable beam tests in October. Harp 5B is based on the 2A monitor design. DB0 has a set of scanning slits, a harp monitor and a Faraday cup; DB10A has a set of scanning slits and a Faraday cup, but no harp. A vertical scanning wire will be installed in DB10A.

Assistance was also given to the IMS-DB11 diagnostics station and the RFQ in-tank diagnostics. The Diagnostics Electronics Support group provided electronics modules, cabling and system integration for all of the beam line 2A and ISAC diagnostics.

Finally, a capacitive pickup was installed at 2AM14 and a toroid was installed at 2AM12 to provide redundant non-intercepting beam intensity measurements for the proton beam in beam line 2A.

## SAFETY AND RADIATION CONTROL

### Licensing

Early in 1998 a submission was made to the Atomic Energy Control Board (AECB) of Canada for a licence to operate ISAC. TRIUMF again made personal representation at the meeting of the Board where the application was initially considered. A licence valid for four years was subsequently granted effective March 31, 1998 in time to allow the initial extraction of proton beam into beam line 2C.

This licence contained a number of conditions and required the written approval of the AECB for the production of radioactive ion beam. Some further documentation concerning handling of irradiated targets and a site visit by AECB staff were required before approval was finally granted November 12, 1998.

### Access Control and Radiation Monitoring

The control of the access for those areas affected by the radiation fields due to the proton beam was incorporated in the existing 500 MeV cyclotron Access Control System. The same design principles were used for what is essentially an extension to the present system. A few minor changes were made in the hardware such as, for example, replacing the traditional 'breakout' bolts on the access doors by a new chain and pin mechanism which should require less maintenance.

The Radiation Monitoring System (RMS) for the 500 MeV facility was extended to ISAC. Five beam-spill monitors, seven air monitors, two neutron monitors and one residual radiation monitor were installed before the start of commissioning. The existing RMS does not have sufficient capacity for the large number of monitors which will be required to monitor the radioactive ion beam losses in the ISAC experimental hall. Work was begun on a new system based on VME hardware and EPICS software. By year-end the work had progressed to the point where several monitors had been built and the system was able to read and write to some of the VME modules.

### Commissioning

The commissioning of ISAC started in late April, with the extraction of a proton beam of a few nanoamperes intensity into beam line 2C. The proton beam was stopped in a temporary graphite beam dump in the beam line 2C tunnel. This allowed measurements to be made to verify the estimates of radiation fields above the shielding due to proton beam losses in this tunnel. Figure 124 shows a comparison of some measurements above the shielding with calculations made using the Monte Carlo shielding code FLUKA. The agreement is better than it appears because the monitor used does not measure the high energy neutron component which is included in the calculation.

Commissioning continued in mid-November with radioactive ion beam production from a CaO target bombarded by approximately 1 $\mu$A of proton beam. No surprises were found and from the radiological viewpoint the commissioning went very smoothly. A target failure during commissioning required that the irradiated target be replaced with a spare target/ion source assembly using the temporary target maintenance station. There was no detectable contamination on the outside of the target module and the dose to personel was lower than expected.

## REMOTE HANDLING

The entire TRIUMF Remote Handling group was committed to various ISAC construction jobs during the year. With responsibilities for target hall shielding fabrication, module services, module assembly, TIS/RIB beam optics component assembly and alignment, as well as conventional ISAC remote handling tasks.

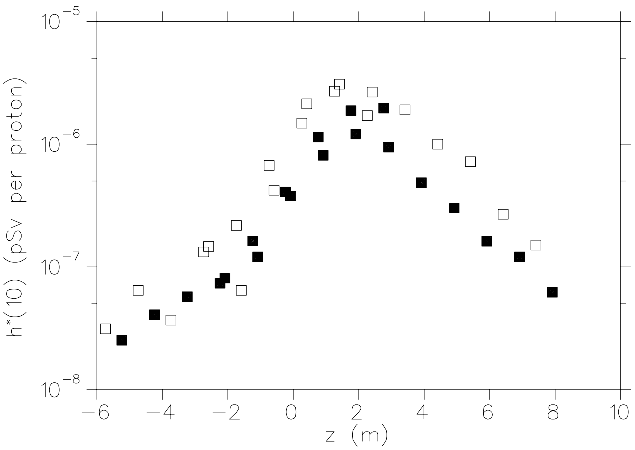


Fig. 124. Comparison of the ambient dose equivalent measured by a moderated $BF_3$ neutron monitor (solid squares) and that calculated using the Monte Carlo code FLUKA (open squares). $z = 0$ corresponds to the front face of the beam dump.

### Service Shielding

Both fixed and moveable radiation shielding for the target hall was designed and fabricated by contractors. Five independent, 18 ton steel/concrete composite shielding blocks, required to shield the operational target station, were constructed, installed and commissioned. When both east and west ISAC target stations are completed these blocks will be shuttled between the operational station and that station under service.

### Beam Lines Servicing

A new design of peripheral-edge water cooled window was developed for, and installed in, the 2A proton beam line. Both 0.010 in. thick stainless steel test windows and a 0.004 in. thick aluminum beam operation window were designed and utilized.

The beam line section between the west vacuum tank and the pre-separator magnet was designed, built and installed This incorporates a rad-hard vacuum gate valve, turbo-molecular vacuum pump and beam diagnostics monitor stack, all remotely handleable for future servicing.

The power and cooling services connections for the ISAC RIB pre-separator magnet were designed, installed, and commissioned.

### Hot Cell Facility

An interim, shielded low-level radiation handling facility was constructed for use until completion of the fully qualified hot cell. This temporary facility provided the operator with 4 in. of steel radiation shielding, moveable Pb glass shielding window ports, and an air exhaust ducting system. The facility was used for removal of the first irradiated CaO target assembly.

Design of the new ISAC target handling hot cell is near completion. Work will begin on construction immediately following wrap-up work on the completed ISAC jobs.

### Remote Crane Handling System

The target hall crane was supplied and installed by the contractor and is now manually operable by wireless remote. Design of a remote operable control system is under way and will be phased in to operation during 1999.

### Alignment

The philosophy for the physical alignment of potentially radioactive target station components was developed and assembly took place during 1998. Using a transfer alignment jig, the true position of the target station module locations w.r.t. the defined proton and radioactive ion beam centre lines can be transferred to a more accessible alignment frame or to the target servicing hot cell. Optical alignment telescopes at either location, with an indexed master reference alignment jig, confirm the positioning of the appropriate module base mounting table. All module target/ion source, beam diagnostics and RIB optics components are then jig-aligned on their base mounting trays during initial assembly to agree with the master alignment jig dimensioning. The concept allows the construction of new interchangeable target station components as well as assuring and conforming to the alignment of component assemblies to be installed in the ISAC hot cells facility.

## BEAM LINE 2A

For reference purposes, Fig. 125 shows the configuration of the final version of beam line 2A. As noted in last year's Annual Report, only the west target will be operated during the first years of operation.

At the end of 1997 the extraction probe, the combination magnet and the first two quadrupoles in the cyclotron vault had been installed and commissioned. Beam had been extracted over an energy range from 472 MeV to 510 MeV to a temporary beam dump that was installed downstream of the second quadrupole. In addition, the 36 ft long vacuum pipe linking the vault section of the beam line to its tunnel section and all quadrupoles and steering magnets upstream of the first 15° dipole in the tunnel had also been installed. During the spring shutdown the remaining elements were installed. The two 15° dipoles and following quadrupole doublet were first installed so as to complete the tunnel portion of the beam line. Emphasis then shifted to the installation of the remaining vault components – the two 27.5° dipoles, a quadrupole doublet and quadrupole triplet, steering magnets, vacuum system, and all related cabling and services. By May, when beam production resumed, all elements of the beam line were operational. However, the beam dump of the target vessel was not yet ready. Consequently, beam was extracted to a (temporary) beam dump positioned at the straight-through port of the first 15° dipole in the tunnel. With this configuration, optics of the beam line – at least to the entrance of this dipole – were verified over an energy range from 480 MeV to 500 MeV. Shortly after this the beam dump was installed in the target module and the remainder of the beam line was commissioned. Figure 126 shows the observed beam profiles at a monitor positioned approximately 1 m upstream of the target position.

The above commissioning runs were undertaken at beam currents of $\leq$10 nA. In November, commissioning runs with beam currents of the order of 1 $\mu$A were performed. Subsequently, the west target assembly was installed and beam intensities of this magnitude were delivered to it. Radioactive beams were extracted from the target and delivered through the mass separator for the first experiments in each of the TRINAT and GPS facilities.

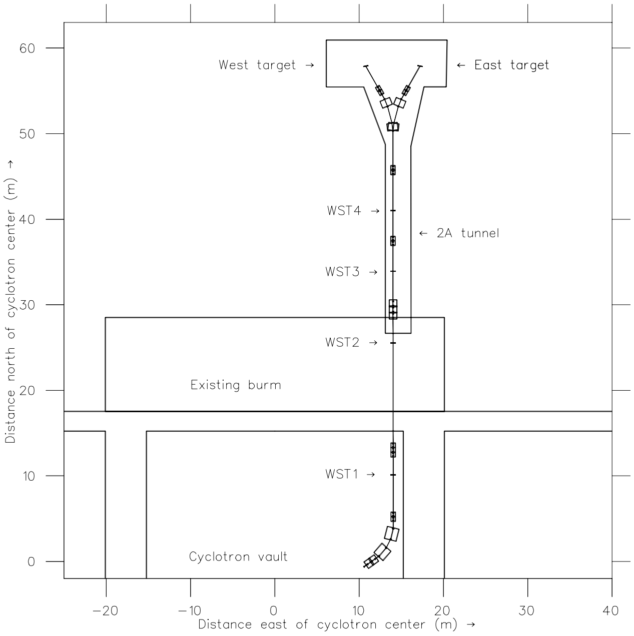
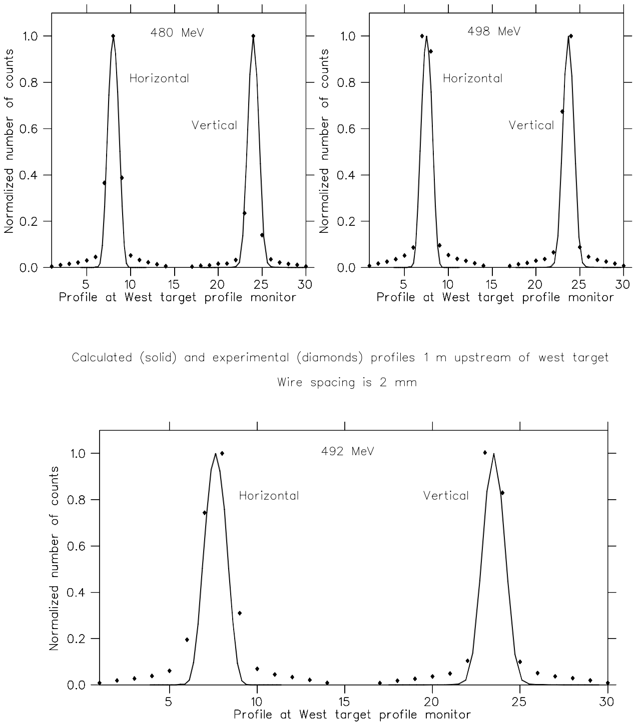


Fig. 125. The configuration of beam line 2A.



Calculated (solid) and experimental (diamonds) profiles 1 m upstream of west target

Wire spacing is 2 mm

Fig. 126. Observed beam profiles approximately 1 m upstream of the west target.

## ION SOURCE TEST STAND

The ISAC ion source test stand was used to determine the thermal and mechanical stability of the surface ionization source prior to its installation in the ISAC target module. Towards the end of 1998, a new version of a TRIUMF ECR source was installed in the ion source test stand to evaluate plasma and beam characteristics in preparation for its future use in the ISAC facilities. The test stand will also be used as a $^7$Li$^+$ source to test components for the polarized $^8$Li$^+$ beam line to be built in the low energy area of ISAC.

### Surface Ionization Source

A prototype target/surface ionization source, support structure and extraction column were tested on the ISAC test stand. The prototype was designed to mimic the geometry in the containment box of the ISAC target module and was an initial iteration of the final design. The prototype target/ion source was heated in the test stand vacuum chamber to a temperature of 2200° C. Target oven temperature was monitored by thermocouples placed in contact with the oven wall and inside the target oven. The target, ionizer and conductor temperatures were also monitored using a 2 colour optical pyrometer through view ports in the vacuum chamber. During heating, the position of the ionizer aperture was monitored using an optical alignment instrument on the ion beam axis. A series of heating cycles showed that the ionizer exit aperture did not move off axis due to thermal stress. The copper conductor and heat shield cooling was shown to be adequate, however, one of the tantalum ionizer leads was found to be much hotter than originally anticipated. The thickness of this component was increased for subsequent designs.

### Electron Cyclotron Resonance Source

A microwave-driven electron cyclotron resonance ion source was installed on the ISAC ion source test stand during the last quarter of 1998. The source is equipped with a 2.45 GHz, 1.2 kW microwave generator operating in cw mode and up to 20 kHz in pulsed mode. The microwave power is fed radially into the resonance cavity of the source with the beam extracted in the axial direction. A flat ECR magnetic mirror region with a non-symmetric low mirror ratio is used to confine the plasma. The unique feature of this source is that the plasma region is much smaller than the physical size of the resonance cavity in order to maximize the efficiency and minimize the ions' transient time. The source is intended to produce short and intermediate half-life radioactive ion beams of volatile elements for low and high energy experiments.

### Polarized $^8$Li Beam

The polarized $^8$Li$^+$ beam planned for the ISAC low energy area will be used to supply beam to condensed matter $\beta$-NMR experiments. The beam will be polarized in the following way. The incoming unpolarized $^8$Li$^+$ beam is neutralized with high efficiency in a sodium-vapour target to create a neutral $^8$Li beam. The neutral atoms are accessible to optical pumping by circularly polarized laser light tuned near the Li $D_1$ resonance at 671 nm (deep red). The optical pumping light is collinear with the fast atomic beam, providing about 2 $\mu$s pumping time over a 1.5 m length. The polarized atoms then enter a helium gas reionizer cell, where they are reionized to $^8$Li$^+$ and are deflected to the experimental station. The sodium and helium cells have been designed and are being fabricated. They will be placed on the end of the test stand, allowing their performance to be measured and optimized using a $^7$Li test beam, before being transferred later in 1999 to the ISAC floor. The helium reionizer is novel, and it is important to measure the ion yield and emittance growth of the beam as functions of helium thickness (atoms cm$^{-2}$) and beam energy. The sodium cell is a jet-type target designed at TRIUMF, similar to one built for the KEK OPPIS upgrade (see POLISIS section), and it will be initially tested on the KEK OPPIS with a H$^+$ beam. Neutralization cross sections of H$^+$ in sodium are well known, providing a way to calibrate the thickness of the sodium vapour as a function of temperature in the cell.

### Target/Ion Source

During 1998, the design for the ISAC target and surface ionization source was finalized and the design concepts tested on a prototype in the ISAC test stand. After modifications and refinements to the design, a commissioning version of the target/ion source was used to produce beams of stable alkali elements for commissioning of ISAC. For on-line use, two targets containing pressed CaO pellets were used for providing radioactive potassium beams to two initial ISAC experiments.

### On-line Targets

Final construction and assembly of the on-line target/ion source design was completed by July. In August, the target/ion source and extraction column were installed and aligned on the ISAC target module. The initial commissioning target consisted of 35 g/cm$^2$ of pressed graphite containing alkali salts for stable beam production. The first stable ion beam at ISAC was successfully extracted to a Faraday cup in the second exit module on September 24. The graphite target continued to be used for beam tuning and mass separator commissioning until November 22, at which time it was replaced with the first experimental target.

The first experimental target consisted of 36 g/cm$^2$ of CaO as pressed pellets on the order of 1 mm thick. ISAC commissioning continued using a stable potassium beam from this target until November 30. At that time, proton beam was put on the target and the first radioactive ISAC beams were measured at a Faraday cup located just short of the TRINAT experimental station. Mass separated beams of $^{36}$K, $^{37}$K and $^{38}$K were observed. The target/ion source operated successfully for a period of 12 days until the surface ionizer failed; the cause of the ionizer failure has not yet been determined.

Table XX. Maximum potassium yields observed from the first CaO target.

| | |
|---|---|
| $^{36}$K | $3.6 \times 10^4$/s/$\mu$A $p^+$ |
| $^{37}$K | $6.6 \times 10^6$/s/$\mu$A $p^+$ |
| $^{38g}$K | $9.8 \times 10^8$/s/$\mu$A $p^+$ |

The second on-line target was prepared consisting of 31 g CaO/cm$^2$ in pressed pellets 2–4 mm thick. After outgassing in situ, the target provided a $^{37}$K beam to the $\beta$-decay experimental station in the ISAC experimental hall. Although further on-line operation of this target was prevented by loss of proton beam due to cyclotron problems, this target remains functional.

## ISAC MASS SEPARATOR

The mass separator was installed and operated for experiment at the end of 1998. $^{37,38}$K were produced on-line and mass analyzed to form the first radioactive ion beam for the new ISAC facility.

The quality of a mass separator is not only the resolving power, but also the enhancement factor. The enhancement factor is a measure of how well the separator succeeds in delivering the desired mass to the focal plane, uncontaminated by unwanted nuclei. It has two parts: the efficiency of delivering the required nucleus, and the efficiency of rejecting the unwanted species. If Iiw and Ifw are the initial and final concentrations of the desired nucleus, and Iiu and Ifu are the initial and final concentration of the unwanted contaminants, the enhancement factor is then, E = I fw/ I iw * I iu/ I fu. The real figure of merit of a separator is its enhancement factor E. It is mainly determined by the tails of the beams. Clearly much effort should be spent on the reduction of long tails. The tail formation is mainly dominated by collision with the residual gas at various places along the mass separator. These give rise to ions with the wrong energy and the wrong momentum that are scattered through the slit, or ions of wrong mass and correct momentum which pass the slit because they have not been fully accelerated. Even the best ion source will not provide a pure ion beam. Ions of neighbouring isobars must be attenuated using an electromagnetic separator. Even if the separation of different masses by a sector magnet is very effective, there is some limit as to how well ions of a different mass m +dm can be separated from the desired ion of mass m. We propose to suppress this type of contamination by adding a second separator stage at different voltage. The contaminants that pass the first sector magnet will have a different magnetic rigidity after acceleration and will not pass through the slits of the second sector magnet. The potential elevation can be as low as 10 kV and does not need to be higher than 60 kV. In our case the main separation stage will be preceded by two quadrupole doublets that allow adjustments to the size of the beam in the $x$ and $y$ planes. Furthermore, the position of the $x$-image can be adjusted to be exactly at the position of the entrance slit by changing the strengths of the quadrupoles. The $y$-image at the separator slit is magnified 10 times, reducing, by the same way, the vertical dispersion thus keeping the magnet gap as small as possible. The image aberrations can be corrected easily. The largest image aberration for a mass separator is usually the aperture aberration, which is proportional to the square of the divergence. Since horizontal divergence is much larger than the vertical divergence, we need to correct only for the horizontal part of the aberration. This can be accomplished with a single curved field boundary. The main mass separation stage is composed of a magnet having a bending radius of 1 m, a bending angle of 135° and a field index equal to 0.5. The resolving power is obtained with this type of mass separator by having a very large dispersion in the $x$-plane while the beam is kept small in the vertical plane.

The ISAC mass separator consists of two mass analysis stages. The first stage is used as a combining magnet for the two stations. It is also used as a preseparator allowing the rejection of most unwanted ions coming from the on-line ion source. The second stage has a much larger resolving power, ~10,000, is installed on a high voltage platform, and combined with the first magnet is very efficient in removing cross contamination coming from low energy tails.

### Target Station and Matching Section

The target and the two exit modules were installed in September. The two exit modules contain the matching optics to the pre-separator magnet. They also housed the diagnostics, which are used to adapt the beam to the pre-separator magnet. On September 24, the first stable beams were produced and the beam optics were tested.

### Pre-separator Stage

The pre-separator magnet was delivered in June. This magnet can accept RIB from either one of the two target stations. The measured mass dispersion of the magnet is in good agreement with the predicted value.

### Mass Separator Stage

The main mass separator was built for the Chalk River facility in the 1970s. The measured resolving power was around 6000. Beam transmission was between 90% and 95% between the pre-separator focal plane and the Faraday cup located just in front of the experimental station. The tune was stable and not sensitive to quadrupole strength variation. The remaining beam dynamics will be measured during commissioning in 1999.

### Diagnostics

Several types of beam diagnostics are used for the mass separator. In the first matching section located in the exit modules where the beam is wide, harp monitors are well suited. Apertures located in front of the harp monitors are used to define the axis of the beam and they come in two sizes, 5 and 10 mm. A Faraday cup measures the beam current extracted from the ion source.

In the other matching sections, because the beam sizes are small, the harp monitors are replaced by scanning wires. The diagnostics at the focal plane of the pre-separator and mass separator include a harp monitor, slits and a Faraday cup. The slit and the Faraday cup are mounted on a platform, which moves across the beam. This feature gives a precise horizontal beam profile. The whole mass separator vacuum is divided in eight sections. The pressure achieved in all sections is lower than $1 \times 10^{-6}$ mbar. The target station was installed during the summer and the first stable beam was extracted September 24. This first test allowed us to find a problem with the high voltage. The problem came from the insulator used as a neutron absorber. We will select another material for the neutron absorber in order to reduce the out-gassing that was creating the high pressure in the vicinity of the high voltage. The beam commissioning of the mass separator started October 23 and the first radioactive isotopes were produced November 30. The proton beam intensity was 1 $\mu$AP on target.

## BEAM COMMISSIONING

The low energy beam transport system (LEBT, see Fig. 127) has been commissioned from the off-line ion source (OLIS) to the RFQ. Using scanning wires and steering elements, the effective lengths of the quadrupoles were determined to within 1%. These results, along with measured distributions in phase space, were then used to adjust the theoretical tunes. When implemented, these gave profiles which were in good agreement with the theoretical ones. As well, the achromaticity of the bend section tunes was verified.

The LEBT acceptance was inferred by varying the steerer correctors and noting the strength required for a 10% loss in beam. The section measured was 5 m long and included 20 electrostatic quadrupoles and 4 45° spherical-electrode electrostatic bends (Fig. 127). The result is shown in a phase space plot, Fig. 128. The blue ellipses are for the horizontal (bend) direction, and the red is vertical. Estimated areas of the encapsulating ellipses are 109 $\pi$mm-mrad in the bend plane and 81 $\pi$mm-mrad in non-bend plane. These are consistent with design. The design acceptance is 200 $\pi$mm-mrad dynamically, but with 1 in. dia. apertures limiting to 100 $\pi$mm-mrad. The philosophy has been to provide sufficient acceptance that the design maximum emittance of 50 $\pi$mm-mrad is easily accommodated.

Initially, the acceptance of the section which matches the beam to the RFQ was only 40 $\pi$mm-mrad. Although this allowed easy on-line monitoring of the beam halo in this section, it did not allow exploration of the RFQ's full acceptance. For this reason, the apertures in this region were opened from 25.4 mm dia. to 31 mm, and the final 'halo' monitor was opened up from 8 mm to 14 mm. The RFQ acceptance figure (90 $\pi$mm-mrad) is shown in Fig. 129, along with the matching section apertures transported to the location of the beam waist at the RFQ entrance.

## RF SYSTEMS

### LEBT Pre-buncher

Instead of a bunching section in the RFQ, the beam is pre-bunched by an external pre-buncher ~5 m upstream of the RFQ. The pre-buncher was designed and built to operate at a frequency of 11.66 MHz plus three harmonics to produce a saw-tooth like waveform across a single gap. The pre-buncher frequency was selected at the request of experimenters to give a longer bunch spacing of 86 ns. Because of a reduction in gain at the higher frequencies, the initial testing was done with only two harmonics. The pre-buncher system was installed and commissioned in the LEBT and operated at full power very reliably for the first beam tests with the RFQ.

#### RFQ system

The ISAC RFQ is an 8 m long, 4-rod split-ring structure operating at 35 MHz in cw mode. The rods are vane-shaped and are supported by 19 rings spaced 40 cm apart. An initial 2.8 m section of the accelerator (7 of 19 rings) was installed and aligned in the 8 m

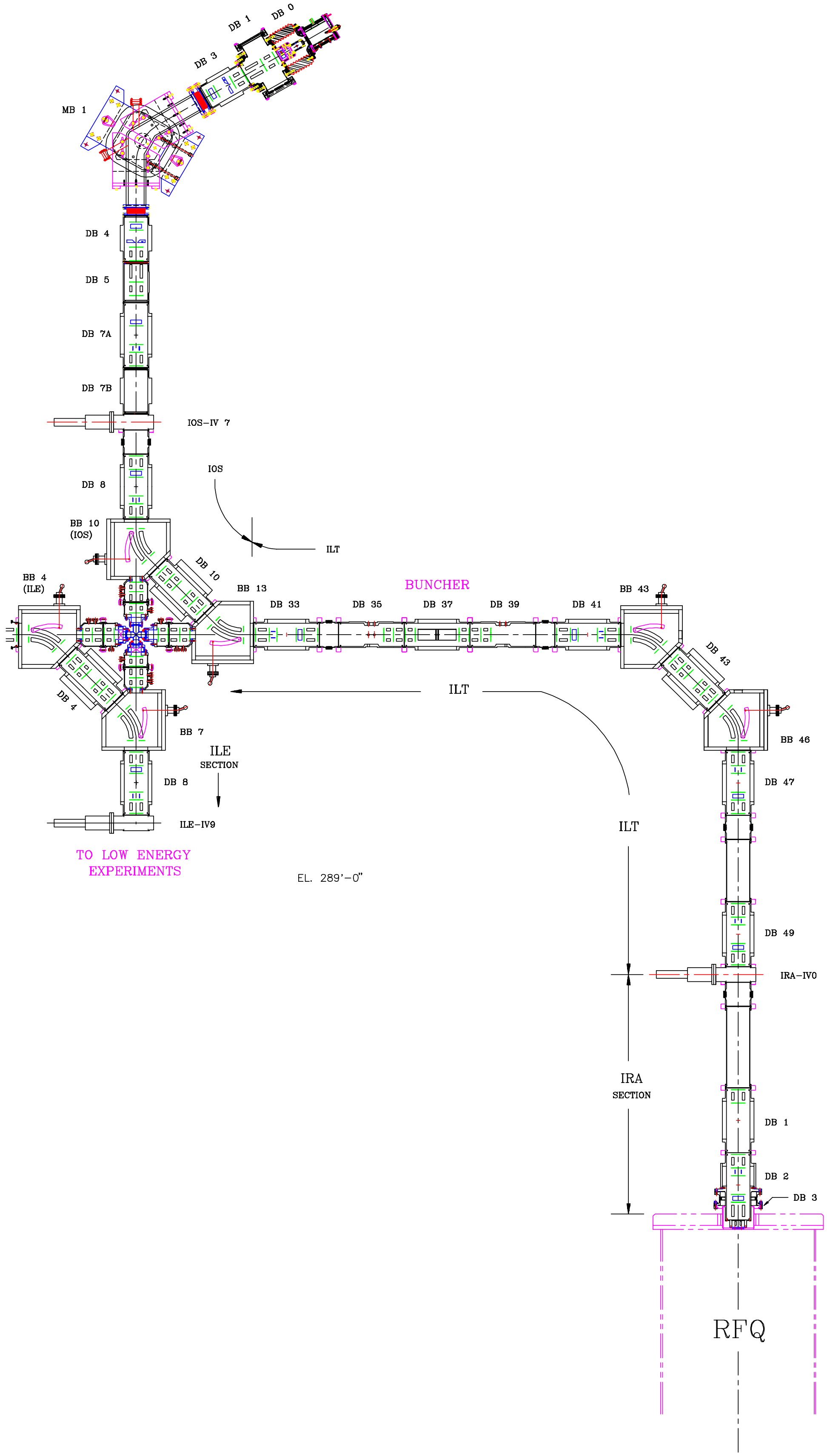


Fig. 127. Layout of LEBT — OLIS to RFQ.

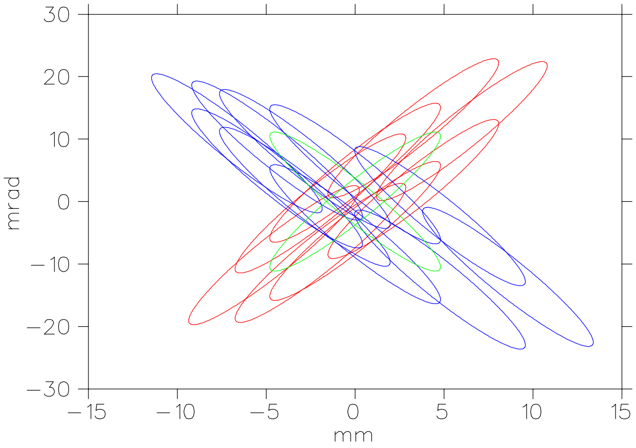


Fig. 128. Measured acceptance of LEBT.

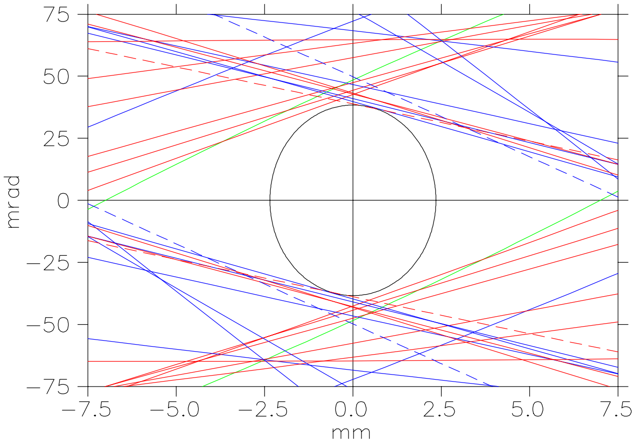


Fig. 129. Apertures in the RFQ matching section of LEBT, along with the theoretical acceptance figure for a 90 $\pi\mu$m emittance.

long, square cross section, vacuum tank (Fig. 130) last year to allow rf and beam tests to be carried out.

The stringent, ±0.08 mm, quadrature positioning tolerance of the four rod electrodes was achieved and a relative field variation along the 2.8 m of the RFQ was measured to be ±1%, using the standard bead pull method. The results of the signal level measurements are compared to MAFIA simulations in Table XXI.

Table XXI. Comparison of measured values to calculated MAFIA values.

| Parameter | MAFIA | Measured |
|---|---|---|
| Frequency (MHz) | 34.7 | 35.7 |
| Q | 15175 | 8700 |
| $R_{shunt}$ (kΩ) | 174.9 | 104.4 |
| $R_{shunt}$ (kΩm) | 489.9 | 292.3 |
| R/Q | 11.53 | 12.0 |

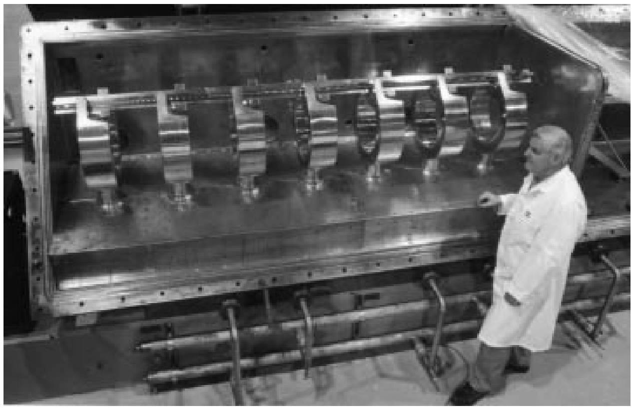


Fig. 130. Seven rings assembled, installed and aligned in the bottom section of the vacuum tank

Because of the size of the mesh used in the MAFIA simulations one would expect the MAFIA simulations to give a lower frequency. Following a three day bake-out at 60° C a base pressure of $1.4 \times 10^{-7}$ was achieved and 76 kV (2 kV above design value) was achieved on the electrodes within four hours at the anticipated power level of 30 kW with an increase in pressure to $4.0 \times 10^{-7}$ torr. We were able to maintain this condition for two hours before our first major amplifier overload occurred. Subsequently, we were never able to achieve the above voltage for the same power. The rf power increased by as much as 40% for the same voltage level of 76 kV. Initially it was thought that this was due to multipactoring in a 7 cm gap between the rf shroud and the tank lid front wall. The problem was eventually traced down to dark currents associated with field emission along the electrodes. The dark currents were essentially eliminated by one hour of high power pulse conditioning. The pulses were 128 $\mu$s long at a rate of 500 Hz at a peak amplitude of ∼100 kV peak. The RFQ operated continuously for 15 hours at nominal voltage plus various runs for 5 and 10 hours before being interrupted by amplifier trips. These amplifier trips were later found to be caused by a failing component in the grid bias power supply. The initial 2.8 meters of the RFQ operated reliably at full power for the beam tests.

The remaining 15 rings (including 3 spares) were assembled using the same cautious procedure as the initial seven rings and are ready for the final high precision EDM (electrical discharge machining) operation on the electrode mounting faces.

## MEBT Rebuncher

The spiral resonator was chosen as the design option for the MEBT rebuncher. The MEBT rebuncher will be operated cw at 35 MHz with a gap voltage of 30 kV. Two designs for the 35 MHz rebuncher, a folded $\lambda/4$ and the spiral were evaluated on the basis of cost, size, rf and mechanical properties. A full-scale prototype of the spiral with water-cooling was constructed to measure the mechanical vibrations as well as rf parameters. The tests reveal that the vibrations are much lower than the allowable limits. MAFIA simulations have been done on the spiral to check the validity of the rf measurements of the prototype. From the computed and measured values of shunt impedance, it is estimated that 1 kW of rf power will be adequate to establish a 30 kV gap voltage in the spiral resonator. Fabrication options are being considered for manufacturing the spiral.

### DTL Triple Gap Buncher

The first DTL buncher, shown in Fig. 131, was developed at INR (Russia) and tested at TRIUMF. It is a triple gap split-ring rf structure operating at 105 MHz. At signal level, 72% of Q-value and frequency within 0.6% of MAFIA simulations were achieved.

The accelerating field distribution measured by the standard bead pull method is compared to MAFIA calculations in Fig. 132. The correlation is within 2.5%.

With cooling water flow of 20 l/min the mechanical vibrations were measured to be in the order of 1 $\mu$m. Following two weeks of fighting vacuum leaks, full power/voltage was achieved on the buncher drift tubes. RF conditioning started with a base pressure of $2\times10^{-7}$ torr. It took $\sim$7 hours to pass through the multipactoring level and another 6 hours to increase the rf power from $\sim$100 W to the nominal level of 8 kW. Although the design parameters are 60 kV gap voltage and 8 kW nominal power, we eventually achieved 85 kV and 16 kW respectively with stable operation limited only by the allowable x-ray production in the test facility area. The longest continuous run at nominal voltage lasted for 80 hours. Taking into account a number of various runs from 5 to 20 hours duration, the buncher operated stable for $\sim$250 hours in total.

Movement of the drift tubes due to the rf thermal load of the ring was measured using a telescope on targets installed in the drift tubes. With a cooling water flow of 17 l/min per arm of spiral, the centres of the drift tubes were displaced by 0.25 mm when full rf power was applied. By reversing the water flow to cool the hottest ring area first, the displacement was reduced to 0.125 mm.

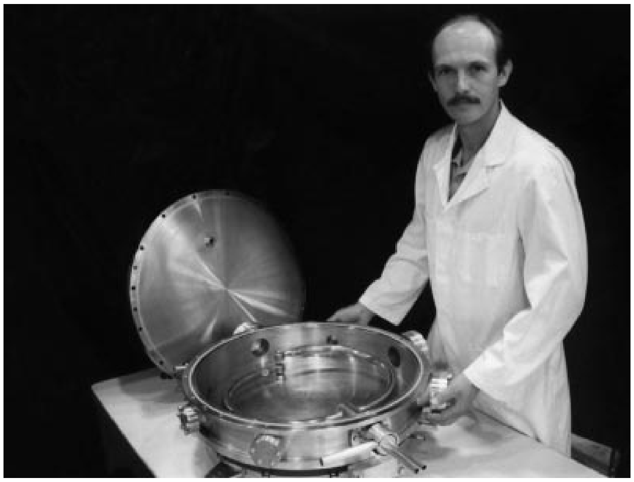


Fig. 131. First DTL Buncher.

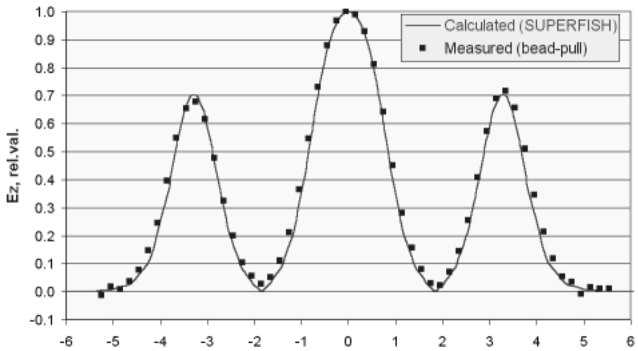


Fig. 132. Field distribution in the accelerating field.

A charged particle current produced and accelerated in the buncher was observed in the diagnostics box, which is attached to the buncher. A field emission (design surface electric field is 13.2 MV/m) is considered to be the nature of this current. Observed current is bunched at the fundamental frequency with an intensity of tens of $\mu$A for the nominal buncher setting.

### RF Amplifiers

Testing of the RFQ power amplifier at medium (80 kW) power levels was successful. Following the installation of the transmission line and the variable line trombone, rf power was successfully fed into the RFQ. The first of 9 rf power amplifiers for the DTL bunchers and cavities was completed and successfully tested into a resistive load at a power level of 22 kW. The amplifier was used to test the first INR buncher. The remaining power amplifiers for the DTL are in the process of being assembled.

### RF Controls

The RF Controls group has been concentrating its effort on the ISAC project. The feedback control system for the ISAC pre-buncher has been commissioned successfully in the first quarter of 1998. The system regulates an 11 MHz signal and up to its fourth harmonic in both amplitude and phase to synthesize a special waveform for beam bunching. Each harmonic is regulated by its in-phase and quadrature phase components using a single DSP. These harmonics are combined together and the resultant signal is used to drive a 1 kW wide band rf amplifier. The output of the amplifier is used to power the pre-bunching cavity, which consists of a set of parallel plates in parallel with a broad band load. Remote controlled operation of the control system is via Ethernet connection using UDP/IP to query status information and TCP/IP for command requests. The RFQ rf control system was commissioned in the second quarter of 1998. A phase locked loop frequency source generates a 35 MHz signal and also uses in-phase and quadrature phase for amplitude and phase regulations. The rf control system has a self-excited mode of operation which uses the RFQ cavity itself as the frequency tuning element and allows the RFQ cavity to run without tuning control. Short period perturbation to the frequency such as minor sparking is ignored by the relatively long time constant of the phase locked loop. The other electrical parameters of the phase locked loop source are chosen for spectral purity as well as enabling smooth transition between self-excited mode and driven mode. The RFQ and the pre-buncher, as well as additional rf cavities in the future, while operating at different harmonics, have to be phase locked together. A frequency distribution unit performs the task of generating these different harmonics with different phase shifts between them. The pre-buncher and RFQ portion of the frequency distribution unit was commissioned in the third quarter of 1998 enabling the pre-buncher and the RFQ to operate coherently.

### Other Developments

#### Bead pull development

New software was written for the bead pull method for measuring the parameters of rf cavities. LabVIEW software was used to develop the program, which enables an on-line view of the bead pull measurement. The program uses a GPIB to communicate with a HP Network Analyzer and at the same time control the bead pull motor via an American Precision Instrument Power/Driver Indexer. A Pentium PC has been dedicated for this purpose and a user manual has been written.

#### Coupling loops

A new coupling loop was developed for the 105 MHz DTL buncher. A Jennings ceramic was chosen as the rf window and the window assembly was adapted to a 3 1/8 in. standard rigid transmission line section. The electric field around the ceramic was optimized using SUPERFISH to provide uniform power loss inside the ceramic. The ceramic window support was water cooled but the coupling loop itself was not water cooled. The coupling loop was installed in the DTL buncher and was tested up to a maximum rf power of 16 kW. The coupling loop was free of multipactor and performed without any failure. A second coupling loop, identical to the above, will be used for the DTL1 tank. Both rf windows were manufactured at TRIUMF. The coupling loop assembly for the buncher was manufactured at INR while the one for tank 1 was manufactured at TRIUMF.

#### Tuners

A frequency tuner driven by a stepping motor was developed for the 105 MHz DTL buncher. Stainless steel bellows provided vacuum to air interface and are shielded from rf. The tuner was tested with rf power of 16 kW in the DTL buncher cavity. A linear frequency tuning range of ±500 kHz could be easily obtained; the nominal required tuning range of the DTL buncher is ±100 kHz. A similar tuner will be used in the DTL1 tank with minor modification of the tuner rod and tuner plate. Both tuners were designed at TRIUMF. The tuner for the buncher was manufactured at INR and the one for tank 1 at TRIUMF.

## RFQ TASK FORCE

The RFQ task force was established in 1996 with the following goals:

- design, build and commission the off-line ion source (OLIS), low energy beam transport (LEBT) and pre-buncher to provide an injector of stable beams for the RFQ
- design and build a shortened version of the RFQ for rf and beam tests, in particular to establish the operating frequency, test operation at full power, and measure the acceptance and matching conditions well in advance of the final commissioning schedule
- design and build a diagnostic station downstream of the RFQ to analyze the accelerator performance.

### OLIS, LEBT and Pre-buncher Commissioning

The off-line ion source (OLIS) is required to commission the LEBT and accelerators as well as supply *analogue* beams to tune the accelerator complex prior to injection with radioactive ions. In addition, stable beams from OLIS will be used for both low and high energy experiments. In 1998 OLIS was routinely used to commission both the LEBT and the 7 ring section of the RFQ. Beams of both $N^+$ and $N_2^+$ have been selected for commissioning due to their ease of production and their masses which give beam experience under both low and high power conditions. The LEBT proves to be easy to tune and matches well the theoretical tune values.

The RFQ design is unique in that the bunching section is replaced by an external buncher in the LEBT, 5.7 m upstream of the RFQ. Up to four harmonics will be used to construct a pseudo-saw-tooth velocity modulation on the beam in a single gap. The fundamental buncher frequency was chosen as 11.7 MHz instead of 35 MHz given that the resultant 86 ns gap between pulses will be important for certain experiments.

The pre-buncher consists of two circular electrodes spaced 8 mm apart forming a single gap with a beam aperture of 7 mm radius. The fundamental frequency of 11.7 MHz and the first three harmonics are individually phase and amplitude controlled and combined at signal level. The signal is amplified by an 800 W broadband amplifier that drives the two plates in push-pull mode with a peak voltage of about 200 V (400 V between plates). Optimization of amplitude and phase of each harmonic results in an almost saw-tooth modulation on the beam velocity. The variation in the gap-crossing efficiency for each harmonic means that the driving voltage is far from a saw-tooth, being dominated by the higher, less efficient harmonics. In fact the present amplifier band width rolls off after 35 MHz and so initial testing was done with only three harmonics. We expect 76% of the beam to be accelerated in the 11.7 MHz bunches at nominal RFQ voltage with $\sim$4% accelerated in the two neighbouring 35 MHz buckets, and 20% of the beam unaccelerated. Adding the fourth harmonic should increase the acceptance by 5%.

The time structure of the bunched beam as measured on a 50 $\Omega$ co-axial fast Faraday cup for one, two and three harmonic bunching is shown in Fig. 133.

The buncher is tuned on-line with beam using RFQ transmission as the diagnostic. The phase of each harmonic is set individually then the voltages are adjusted to previously calculated values followed by empirical optimization. The tuning is straightforward and the performance matches the predictions of simulation studies.

### The RFQ Interim Beam Test

The final RFQ electrodes will span 7.6 m with 19 modules each consisting of one ring and 40 cm of electrodes. In 1998 an interim beam test was completed with the first 7 ring section (2.8 m), accelerating beams to 55 keV/u. A schematic of the test set-up is shown in Fig. 134. An rf short is placed after the seventh module to confine the rf fields. Eight electrostatic quadrupoles are used to transport the beam to a diagnostic station downstream of the RFQ tank. A Faraday cup and profile monitor assembly are placed just after the RFQ short and again in the middle of the electrostatic transport after the fourth quadrupole. The diagnostic station shown in Fig. 134 includes a Faraday cup, a transverse emittance rig and a spectrometer consisting of an object and image slit and a 90° bending magnet.

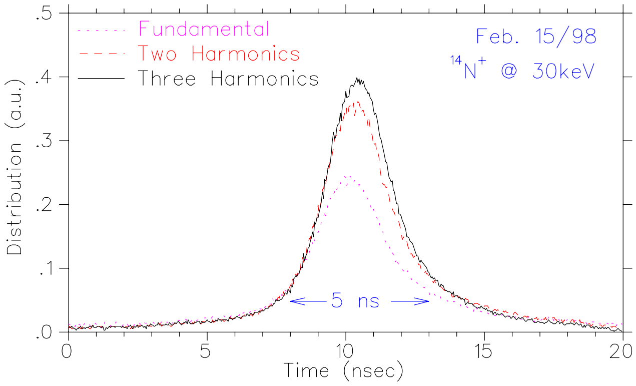


Fig. 133. Beam bunches measured on the fast Faraday cup in LEBT for one, two or three harmonic bunching.

The beam from the RFQ is brought to a double waist after the first four quadrupoles and again at the exit of the RFQ. The quadrupoles are each 30 cm long with a 2.5 cm half aperture and require maximum voltages of just under 10 kV for $A = 30$. For mechanical reasons the RFQ vanes are orientated at 45° to the horizontal. As a consequence the first four electrostatic quadrupoles are also at 45°. The transverse reference frame is rotated to the normal after the first double waist where the beam is round. The quadrupoles when tuned act as an energy filter; the unaccelerated beam is lost in the first few quads. Therefore the transmission difference between the first Faraday cup and the second marks the capture efficiency of the RFQ.

The diagnostic station is designed around a $\rho =$ 1.5 m analyzing magnet with a dispersion of 3 cm/%. (The magnet was generously donated by the Nuclear Physics Institute in Rez, Czech Republic.) The magnet is placed symmetrically between horizontally defining object and image slits 1.5 m upstream and downstream of the magnet respectively. A Faraday cup just downstream of the image slit records the transmitted beam and the energy and energy spread are derived from the magnetic field. A slit and harp transverse emittance rig is positioned upstream of the magnet. An Allison type emittance rig is located in the LEBT to record transverse emittances before acceleration.

Both rf and beam tests have been successfully completed. The RFQ was operated in cw mode for all beam tests. The operation of the RFQ at peak voltage (74 kV) is stable. A summary of the RFQ rf tests is given on page 156. Beams of both $N^+$ and $N_2^+$ have

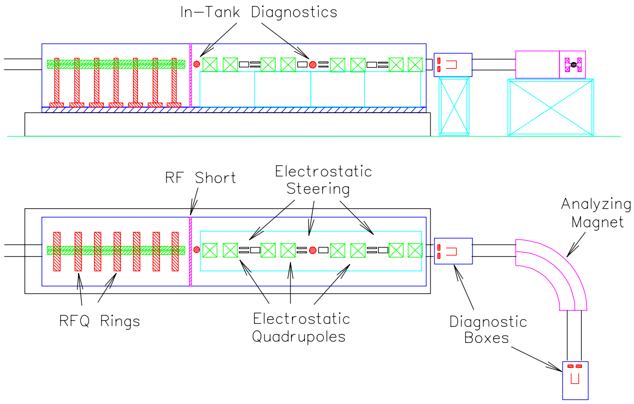


Fig. 134. Schematic diagram of the set-up for RFQ task force beam test.

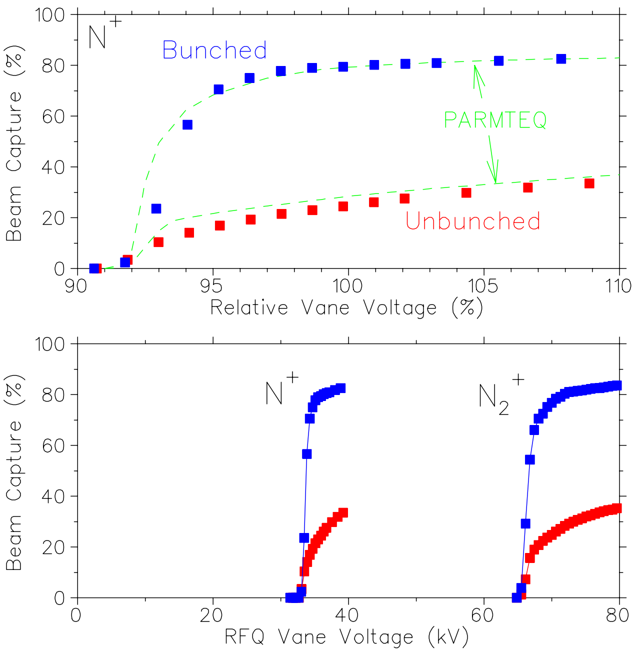


Fig. 135. Top: RFQ beam test results showing capture efficiency for beams of $N^+$ as a function of relative vane voltage. The beam capture for both bunched and unbunched initial beams is recorded (squares) and compared with PARMTEQ calculations (dashed lines). Bottom: the results for both $N^+$ and $N_2^+$ are plotted with respect to absolute vane voltage.

been accelerated to test the RFQ at both low and high power operation.

Beam capture as a function of RFQ vane voltage measurements has been completed for each ion and for both unbunched and bunched input beams. The results are given in Fig. 135 (squares) along with predicted efficiencies based on PARMTEQ calculations (dashed lines). The RFQ capture efficiency at the nominal voltage is 80% in the bunched case (three harmonics) and 25% for the unbunched case in reasonable agreement with predictions. The capture for one harmonic and two harmonic pre-bunching is 63% and 74% respectively.

The energy of the beam as measured with the analyzing magnet is 55 keV/u. The energy spread for the bunched and unbunched cases was measured at ±0.4% and ±0.7% respectively and compares well with PARMTEQ predictions (Fig. 136).

Transverse emittances were measured before and after the RFQ. The results show that when the matching is optimized the emittance growth in both planes is consistent with zero for an initial beam of 15 $\pi$mm-mrad. A summary of the results for $N^+$ is presented in Fig. 137. Space charge forces limited the longitudinal acceptance for currents above $\sim$1 $\mu$A but did not impact the transverse emittance.

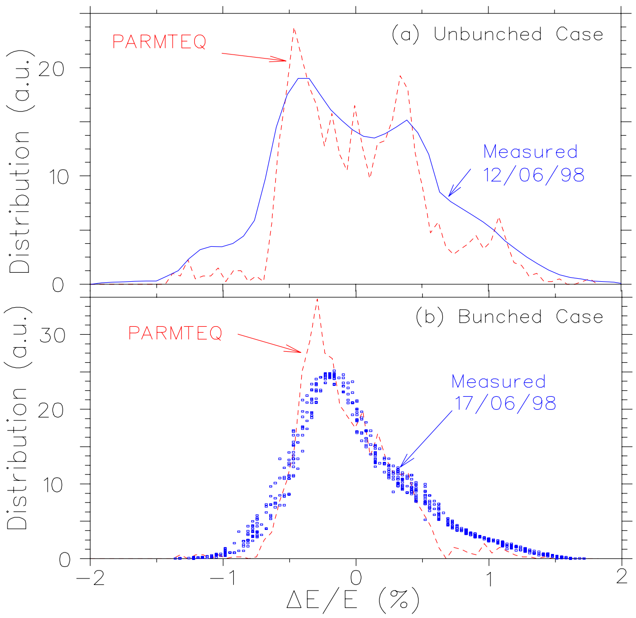


Fig. 136. Results of energy spread measurements of accelerated $N^+$ beams for both (a) unbunched and (b) bunched cases. PARMTEQ simulation results are plotted for comparison.

The transverse and longitudinal acceptances were explored with a so-called ‘pencil beam’ defined by two circular apertures of 2 mm each separated by 0.7 m placed in the RFQ injection line. One steering plate was available downstream of the collimators to steer the pencil beam around the RFQ aperture.

The test shows an interesting feature of an RFQ with no bunching section. The well known two term potential function gives the fields near the axis of an RFQ. From this potential function the spatial component of the accelerating field is given by

$$E_z = \frac{kAV}{2} I_o(kr) \sin kz$$

where $k = 2\pi/\beta\lambda$ and $\beta$ is the relative particle velocity. The formula shows that off-axis particles experience stronger fields than on-axis particles, particularly at injection where $\beta$ is small. In the ISAC RFQ the design synchronous phase is fixed at $-25°$ at the nominal voltage but for off-axis particles the synchronous phase opens up and the acceptance grows as a result. A typical measure of the synchronous phase is the cut-off voltage, that voltage below which no acceleration can occur. Beam transmission as a function of RFQ voltage was measured for various steering plate voltages. Results for a centered beam and two off-centered cases are plotted in Fig. 138. The two off-centered cases correspond to coherent amplitudes measured at the RFQ exit of $A_c = 1.7$ mm and $A_c = 2.7$ mm. The results show clearly the reduction in the cut-off voltage for increasing amounts of off-centering. It is also clear that

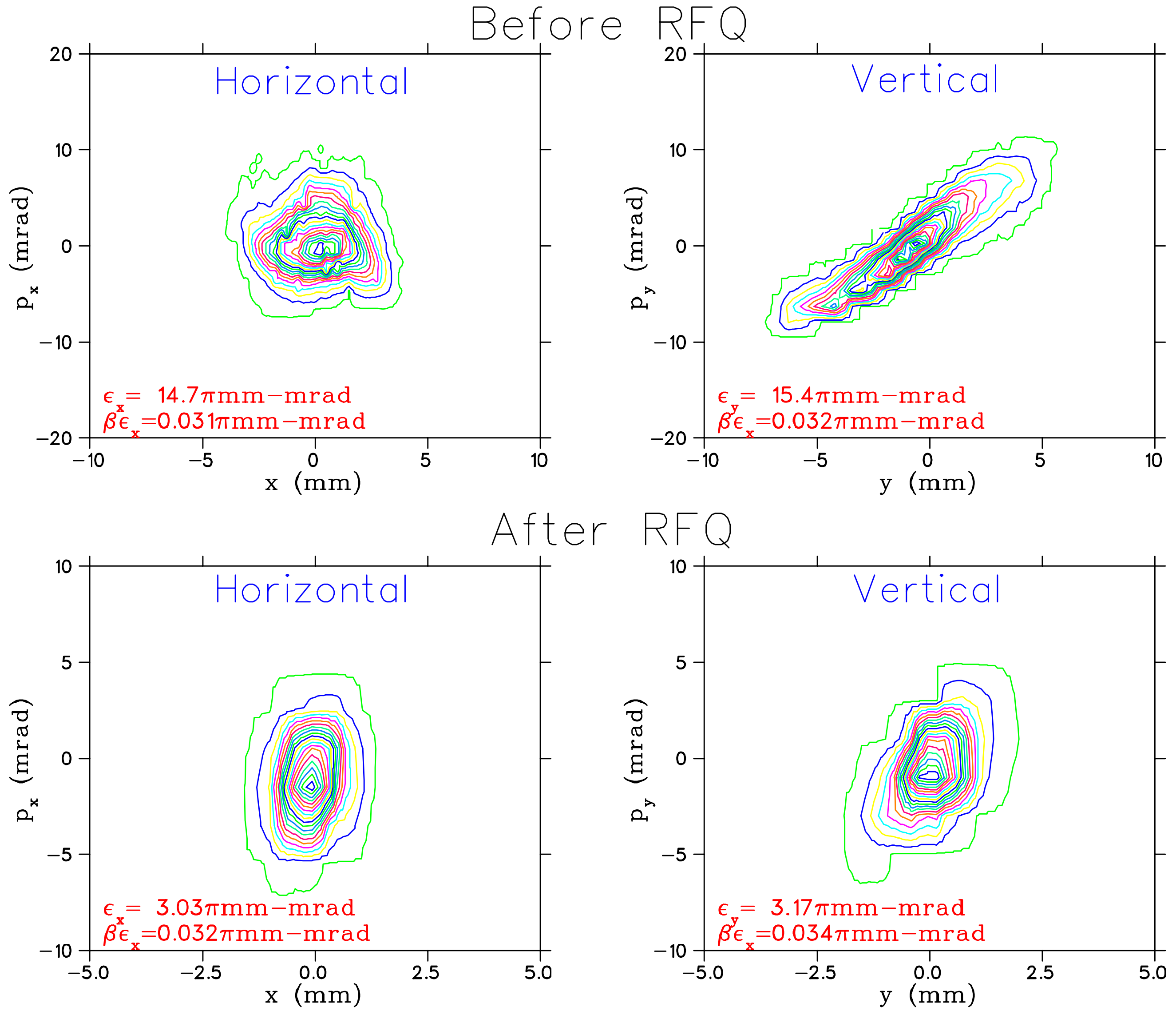


Fig. 137. Transverse emittance measurements (4RMS values) for $N^+$ before and after the RFQ. The normalized emittance values are also displayed.

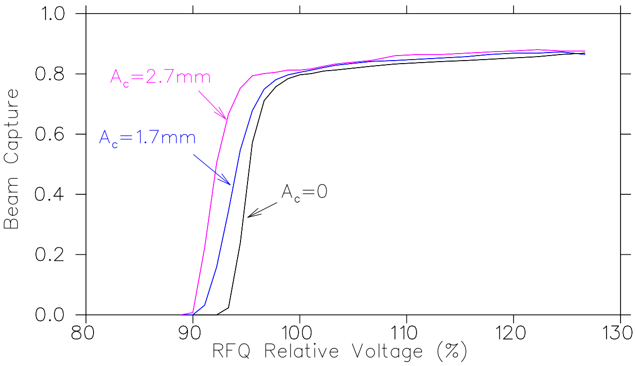


Fig. 138. Transmission of pencil beam as a function of RFQ voltage for a centered beam and two cases of off-centered beam with vertical centering errors at RFQ exit of 1.7 and 2.7 mm.

as the voltage nears cut-off the acceptance difference between on-axis and off-axis particles is enhanced.

In conducting the transverse acceptance studies we have determined a method to measure the magnitude of the centering error in the RFQ. The off-center small emittance beam passes through the RFQ making coherent oscillations about the RFQ axis. The transverse phase advance per unit length is dependent on the RFQ voltage. The centering error can be determined by scanning the RFQ voltage through a span equivalent to a change in transverse phase advance of 2 $\pi$ and recording the final beam position. The rate of phase change with RFQ voltage is also a useful diagnostic. It can be used to determine if the centering error was present at injection or was developed during acceleration with a dipole error.

The pencil beam was injected into the RFQ and the transmission and centering error recorded for various steering plate settings. Beam position as a function of RFQ voltage is given in Fig. 139 for three different steering plate settings 0, 400 V and 600 V. The two deflected cases correspond to the transmission data plotted in Fig. 138. Based on the steering/transmission data the transverse acceptance was estimated to be ≥140 $\pi$mm-mrad.

The longitudinal acceptance was measured for both a centered and an off-centered beam ($A_c = 2.7$ mm) at the nominal RFQ voltage using the pencil beam. The energy of the injected beam was varied at the source. For each energy step the phase of the bunched beam was varied with respect to the RFQ phase and the capture efficiency was recorded for each step. The settings where the acceptance dropped to 50% of the peak value were used to define the longitudinal acceptance contour. The acceptance of the centered beam was estimated to be 180 $\pi$%-deg at 35 MHz or 0.3 $\pi$keV/u-ns. The acceptance opens up for off-centered beams with values of 400 $\pi$%-deg at 35 MHz or 0.7 $\pi$keV/u-ns. The expected longitudinal acceptance based on PARMTEQ simulations is 0.5 $\pi$keV/u-ns. Beam transmission contours for both the centered and off-centered cases are presented in Fig. 140. The tail in the acceptance plot seen in the upper right corner of the stable region is typical of linear accelerators.

The increase in accelerating field strength for off-axis particles provides a large stable saddle point in the longitudinal motion. One problem with having stronger off-axis fields, however, is that the transmission improves (at the expense of beam quality) as the beam moves off-centre making tuning difficult. An optimization procedure was developed where the LEBT is tuned at high RFQ voltage for maximum transmission then the last steering plates and matching quads are re-tuned at an RFQ voltage near cut-off to achieve a local minimum in the transmission. The procedure results in not only a centered beam but also a matched beam since a matched beam will see lower accelerating fields on average.

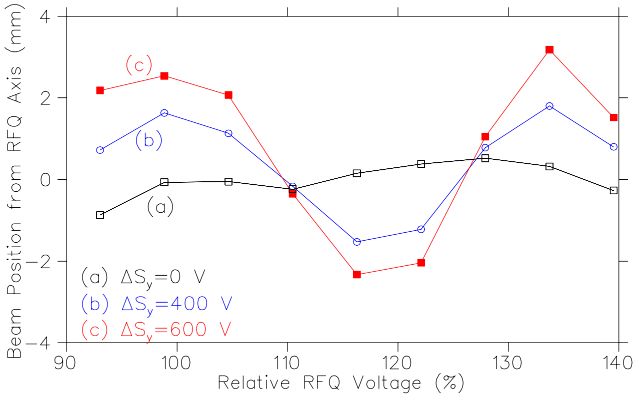


Fig. 139. Beam position at RFQ exit as a function of RFQ voltage for three different steering plate strengths – 0, 400 V and 600 V.

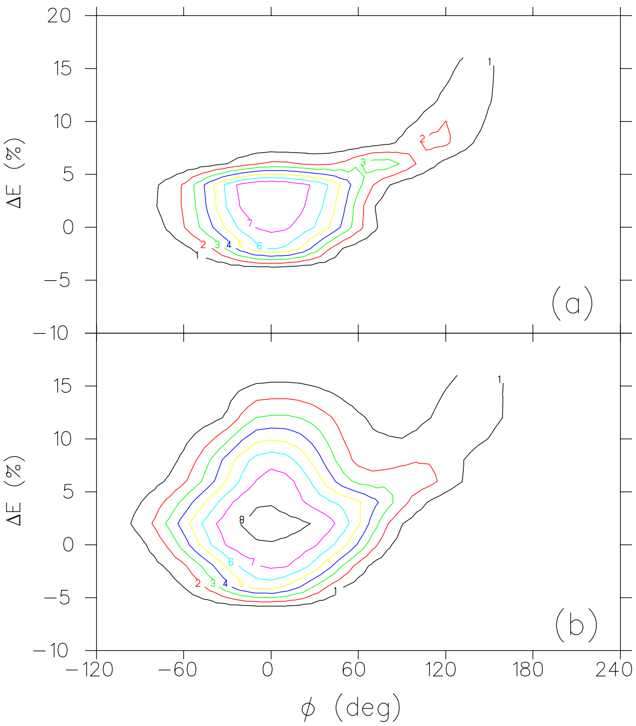


Fig. 140. Measured longitudinal acceptance of the RFQ for a centered beam and an off-centered beam ($A_c = 2.7$ mm).

The matching is effective in reducing the final transverse emittance. Larger unmatched beams are subject to a spread in the radial tune due to the radial variation in the field strength and associated emittance growth. An example is shown in Fig. 141 where the last matching quadrupole is varied and the final emittance out of the RFQ is measured. The minimum in emittance corresponds to the saddle point in the transmission associated with a centered beam.

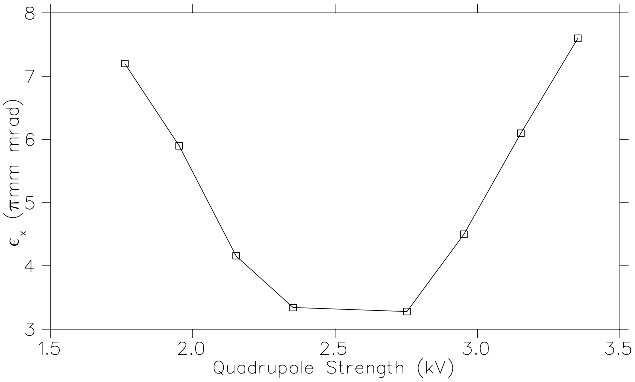


Fig. 141. Final horizontal emittance as a function of the strength of the last matching quadrupole.

In general the beam test results demonstrate a strong confirmation of both the beam dynamics design and the engineering concept and realization and give us full confidence in proceeding with the installation of the remaining twelve split rings.

## MEDIUM ENERGY BEAM TRANSPORT

Further optimizations of the medium energy beam transport (MEBT) have evolved to meet various design issues. In particular, steering magnets and beam-pipe flanges and bellows have been added to the section forcing quadrupoles to shift as required. As well, it has been decided to use Chalk River 18 cm quadrupoles throughout the MEBT replacing the few TRIUMF designed 'bunny' quadrupoles that were initially specified. Finally, shielding is being incorporated around the collimators after the RFQ, the chopper slits and the charge selection slits.

Combined horizontal/vertical steering magnets procured from Chalk River will be used in the initial MEBT section to the stripping foil. Shorter TRIUMF designed vertical steering magnets will be used in the charge selection section. Longitudinal space is very tight in the matching section before the DTL. For this reason a short $x-y$ steerer will be placed just after the rebuncher and the two middle quadrupoles will be equipped with separate steering coils.

An engineering layout has been completed and is displayed in Fig. 142.

## DTL QUADRUPOLE TRIPLET

Quadrupole triplets are positioned between IH tanks to provide transverse focusing. In particular, the triplets are used to refocus the diverging beam at the end of an accelerating section in such a way that the beam stays circular throughout the acceleration with a waist occurring approximately mid-way along an accelerating section. In order to maximize longitudinal acceptance it is desirable to minimize the triplet length. The challenge is to build strong gradient triplets and position and support them in the minimum longitudinal space. The strength, length and alignment tolerances of the quadrupole triplets have been specified. The engineering design of the quadrupoles is well under way and the intertank connections and triplet support have been detailed.

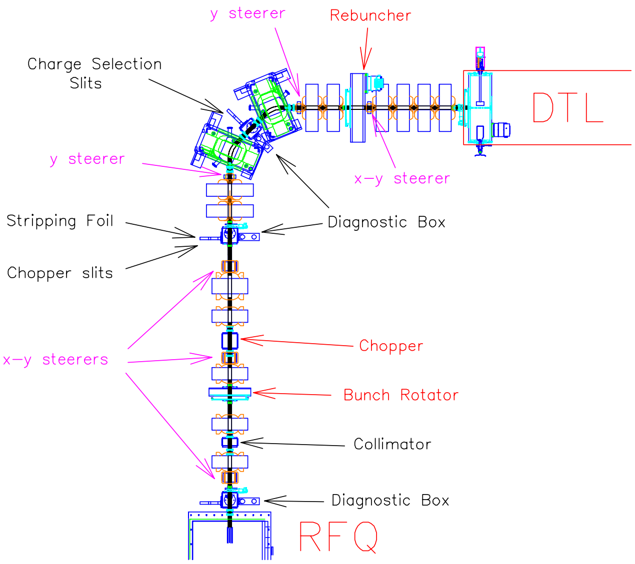


Fig. 142. Engineering layout of the medium energy beam transport.

Even though the initial DTL design was based on ions with mass to charge ratios varying from $3 \leq A/q \leq 6$, recent discussions on a future expansion of the ISAC facility (ISAC-II) suggest that future operation of the DTL at $A/q = 7$ would be desirable. It is thought that the required accelerating gradients could be made available, at least in pulsed mode, as long as the quadrupole triplets are sufficiently robust. To this end a capability of focusing this heavier beam was included in the quadrupole specification. The length and strength values for the quadrupole are based on a gap between quadrupoles (between magnetic edges) of 50 mm. Triplet specifications are as follows: quadrupole lengths of 65, 95 and 65 mm and strengths of 65, 75 and 65 T/m.

The resultant beam envelopes through the DTL are shown in Fig. 143 assuming a transverse emittance of 0.15 $\pi$mm mrad. Based on these results a quadrupole bore aperture of 24 mm was chosen. The focusing gradient in each quadrupole should be uniform to ±1% over ±8 mm of this aperture.

A sketch of the inter-tank region is shown in Fig. 144. The quadrupole assembly will be at air with a stainless steel jacket surrounding the end caps joined at one end to the beam tube and ending with a flange and bellows section to form a vacuum connection with the upstream tank and the downstream buncher. In this way the quadrupole triplet can be removed for

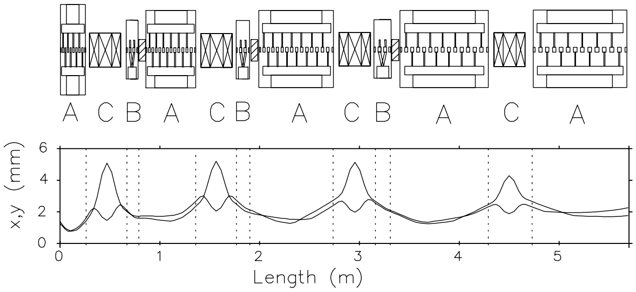


Fig. 143. Transverse beam size in the ISAC DTL assuming a transverse emittance of 0.15 $\pi$mm mrad.

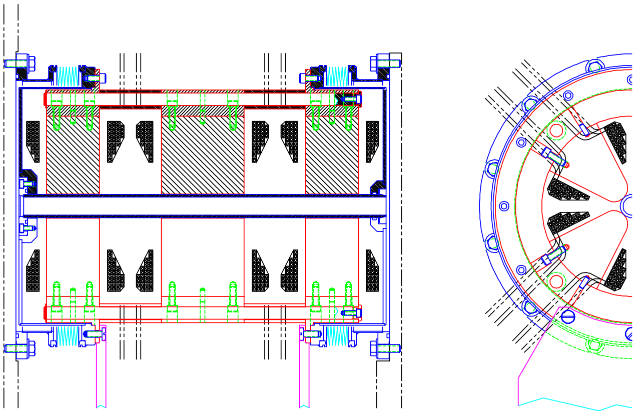


Fig. 144. Assembly drawing of the ISAC-DTL quadrupole triplet.

servicing while still occupying the minimum longitudinal space. The buncher and diagnostic box are made as a single piece. The diagnostic box is connected to the upstream box by a large O-ring flange.

The steering requirements for the DTL were investigated. Due to space restrictions, independent dipole windings will be added on the centre quadrupole of each triplet to steer the beam. Studies indicate that the imperfect steering fields lead to a small yet acceptable transverse emittance growth.

Alignment tolerances are set by demanding that the beam displacements from misalignments are small compared to the beam size or at least small compared to the acceptance. Practically speaking the quads should be aligned to better than 0.1 mm accuracy with a pole placement better than 0.1 mm.

## HIGH ENERGY BEAM TRANSPORT

The design of the high energy beam transport (HEBT) has seen minor alterations in the last year mostly due to changes in the DRAGON footprint. We have moved the take-off angle from 30° back to the original 22.5°. A second 22.5° feeds the beam to the DRAGON target. The length of this achromatic section has been shortened. The second dipole in the achromat is defined as a switching magnet to allow a reverse achromatic bend of 18° to feed a second experimental area. Provision has also been made to allow the installation of a post-accelerator after the DRAGON take-off for the ISAC-II expansion.

In order to reduce HEBT costs, an 11.7 MHz rebuncher is under development. The idea is to use an 11.7 MHz rebuncher for low $\beta$ particles and a MEBT style 35 MHz rebuncher for high $\beta$ particles. Each buncher would be placed after the periodic/diagnostic section ∼12 m downstream from the DTL and would remove the requirement of multiple 35 MHz rebunchers spaced throughout the HEBT.

Further changes in design will occur as the plans by experimental users solidify.

## BEAM DIAGNOSTICS

The most evident progress in 1998 was the provision and installation of cables, electronic modules and racks to service 80 new diagnostic devices installed in the separators and LEBT, between the production target and the TRINAT and Yield experiments. The assembly of mechanical hardware was shared between the ISIS and Probes groups; the latter concentrating on specialty items such as equipment in the exit modules and in diagnostic boxes at the origin and image of separators.

Several electronic modules were either designed and prototypes tested or taken from the prototype stage to a properly engineered version using custom printed circuit boards and design programs such as PROTEL. These modules include:

- QSX/W, a higher, 1 kHz, bandwidth version of the popular QSX multi-range quad amplifier suitable for scanning monitors with moving beam sensors.

- Module 0926 which sets the timing of start, sample and stop pulses for scanning monitors. A potentiometer interface card 0924 for the standard ISAC rotary scanning profile monitors; this interface card reduces the noise on the position signal. Module 0927 is an isolated 6 channel 10 V precision reference power supply suitable for the potentiometers and any other floating or biased electronics attached to beam sensors. Module 0933 is an opto-isolator unit to enable the signal from MWIC or harp monitors to bridge between integrator (0518) units in one rack and digitization or display units in other racks at a different potential.

- Four small preamplifiers and associated power supplies with a output of 10 mV/pA; (the most sensitive range of the rack mounted QSX is 1 mV/pA). The preamplifiers may be located close to the beam sensing element, even placed in vacuum, and may be floated with respect to ground potential. The bandwidth, 3 db, is 12 Hz for one pair and 70 Hz for the other. They have been used on the ion source test stand and on ISOL. We will judge their operation with low RIB currents in ISAC next year before going into production.

Several tests were performed on new monitor designs or on components which may be incorporated into beam diagnostic instruments. Some of these tests utilized ion beams. The tests included:

- Measurements of the scan to scan reproducibility in position of scanning profile monitors. The actual position was determined by the beam sensing element intercepting the light beam from a fixed laser diode. A number of passes were made for each condition of operation and the standard deviation of the values obtained from the position readback calculated. The jitter results were:

  Oscillating scanner with rotary drive: $\sigma$=120$\mu$m
  Linear scanner with pneumatic drive: $\sigma$=70$\mu$m
  Linear scanner with stepping motor and tensioned belt: $\sigma$=8$\mu$m

- A fast Faraday cup was used in the commissioning of the test 7-section RFQ to measure the longitudinal distributions of the beam at entrance and exit. The output was amplified by a gain of 20 using a Philips 774 amplifier with 2 GHz bandwidth and observed by a TDS 820 oscilloscope. Signal averaging permitted clean data to be obtained at peak currents of 50 $\mu$A with 1 $\mu$A noise. The width of the beam bunch at exit was 3 ns, the value expected for that location. There was no reason to suppose that the frequency response of the cup did not exceed that of the amplifier. Both the charge collecting electrode and a slit upstream of the cup could be biased. It was determined that there was a bunch of electrons emanating from the slit jaws and the most accurate operation was obtained with the collector at 0 V and the slit at +50 V. This cup was donated by Dr. Poggi of LNL, Italy. A new FFC has been designed for MEBT; the design permits the entrance grid that localizes the beam field to be biased if desired.

- A full size, full power, prototype has been constructed of the bunchers to be installed between tanks of the drift tube linac. Electrons had been observed on the axis of this buncher and there was some concern that they may introduce spurious signals on beam diagnostic equipment nearby. The 105 MHz buncher has been designed to produce a sinusoidal electric field of amplitude 13.2 MV/m. We measured electron currents from 2 to 20 $\mu$A dc at this field level, the current falling as the buncher was conditioned and as the vacuum improved. The electrons were in bunches about 1 ns wide with an energy >> 1 keV. The current was a very steep function of buncher field and its behaviour was consistent with the assumption of field emission as the source; however, our measurements were not precise enough to make a definite statement. We also saw evidence of positively charged particles and copious low energy electrons. Fortunately it should be possible to commission and operate the DTL while turning off the buncher and tank closest to the diagnostic box. If this should not be possible then measures will have to be taken to deflect or suppress these stray charges since their current may exceed that of the weak ion beams.

Some theoretical calculations have been performed; these include:

- Range vs. energy graphs have been produced for ions of interest to ISAC. Ranges in a few materials from water to lead were calculated for ions from helium to xenon over energies between $10^{-5}$ and $10^{2}$ MeV/u. The data in the present TRIUMF Handbook [Greeniaus, 1987] are for lighter ions and energies above 1 MeV/u, i.e. a region where only electronic or ionization stopping need be considered and nuclear stopping may be neglected.

- Secondary electrons are produced when ions hit a wire. A monitor has been designed to measure the distribution in time of the beam by accelerating a portion of these electrons into a microchannel plate. Trajectories of both electrons and ions have been calculated in the field of the monitor and the calculations show that the broadening of resolution due to variations in path length is less than 50 ps from each source except for low energy ions in LEBT where the contribution to resolution may be 300 ps. This monitor should give time information at very low currents; it has not yet been constructed since the FFC is adequate at present.

- A pair of linear profile monitors operated successfully in the RFQ tank downstream from a shield terminating the field of the 7 section test RFQ. The carriage of each bore 3 wires at 45° to each other. A pseudo-tomography program was written to show an approximation to the beam density distribution in the $X$-$Y$ plane in addition to the usual projections on the $X$ and $Y$ axes.

- Beam power limits were calculated for some fixed and moving beam sensors.

- Parameters, including space charge, that determine the bias voltage required on monitors, such as Faraday cups, were considered. It was concluded that the standard TRIUMF dc power supply should provide 300 V.

## ISAC CONTROLS

Detailed design and implementation of the ISAC control system proceeded fairly smoothly all during the year targeting and achieving the following milestones:

- Beam line 2A vacuum system control, beam monitor control and power supply on/off control in May
- RFQ vacuum system, in-tank optics and in-tank diagnostics in June
- MEBT vacuum system and diagnostic station in July
- Target station vacuum, optics and diagnostics control in September
- Pre-separator and mass separator vacuum, optics and diagnostics control in October
- Vacuum, optics and diagnostics control for low energy beam transport from mass separator to TRINAT and GPS experiment in November/December.

As of end of the year, the ISAC control system (not counting beam line 2A) contains approximately 2500 digital and 1600 analog control channels.

### Hardware

Three more VME crates were installed to house the IOCs for targets, mass separator and LEBT, a fourth VME crate is used for beam line 2A. For beam diagnostics, we started using TRIUMF designed VME modules, which are described in more detail in the Electronics Development section of this Annual Report. The VQSX, an 8-channel variable gain beam current amplifier with 100 kHz transient digitizing capability, proved very successful in measuring beam profiles with harps and wire scanners at sub-nA currents. It is also used to digitize harp readouts. Stepper motor control for pre-separator and mass separator diagnostics devices was implemented using commercial controllers (OMS58). This work is described in more detail in the Electronics Services section.

For beam line optics, 170 more device controllers were mounted on high voltage power supplies and added to the CAN-bus network. Special versions were developed to control the pre-separator and mass separator supplies, which were acquired from Chalk River National Laboratories. Both on the targets and the RFQ, sparking problems were encountered which still have to be further investigated.

The vacuum sub-system controls for RFQ and MEBT were added to the off-line ion source PLC. A second Modicon Quantum Series PLC was installed for the vacuum sub-systems for targets, mass separator and LEBT. Six more PLC breakout cabinets were prewired and tested in Trailer Gg and installed in the electrical services room, on the mass separator platform, in the TRINAT ante-room and on the experimental hall mezzanine.

For beam line 2A a third Modicon PLC was installed for control of the vacuum system, motion control of beam monitors and power supply on/off controls. The PLC system is used to adapt the beam line devices to the control model of the TRIUMF central control system and to provide interlock functions in a similar way as relay based hardware is used on the older beam lines. PLC data and commands are exchanged with the central control system via a VME based SDLC link. One PLC breakout cabinet each was installed for devices located in the vault and beam line 2A tunnel respectively.

At the beginning of the year we encountered random IOC crashes, which were eventually traced to the VME based Modicon PLCs. The PLC CPUs contained a design flaw in their interface to the VME bus which made them unusable in our environment. A temporary work-around was found and an exchange was negotiated with the supplier. Three of the four VME PLCs were exchanged with Ethernet based models by the end of the year. The final exchange will take place in January, 1999. The new models communicate via TCP/IP instead of through the VME back-plane, which results in an increase of overall system robustness.

For commissioning ISAC, the ion source control room next to the electrical services room was set up with a temporary control console. It consisted of two PCs with three monitors each using X-terminal software. Two SUN workstations were set up as production servers in the ISAC control room. A 24-port Ethernet switch dedicated for ISAC controls was set up in the communications room. Initially this was fed via the temporary thin-wire connection to the ISAC building. Later during the year the final site connection was installed and the remaining thin-wire connections are being phased out.

An overview of the control system hardware configuration at the end of the year is given in Fig. 145.

### Software

During this year we were able to benefit fully from the high productivity of the EPICS system, both during development and especially during testing and commissioning where several scheduled weeks were collapsed into a few days.

On the operator interface level a large number of overview screens and detailed device control panels were produced following the conventions developed during the previous year. Associated configuration scripts and backup/restore scripts for all sub-systems were written. Efforts were made to automate some of the more clerical aspects of EPICS user interface production. 2D plots for pre-separator and mass separator scans were implemented and the EPICS strip-chart tool was installed and used. Parameter logging was

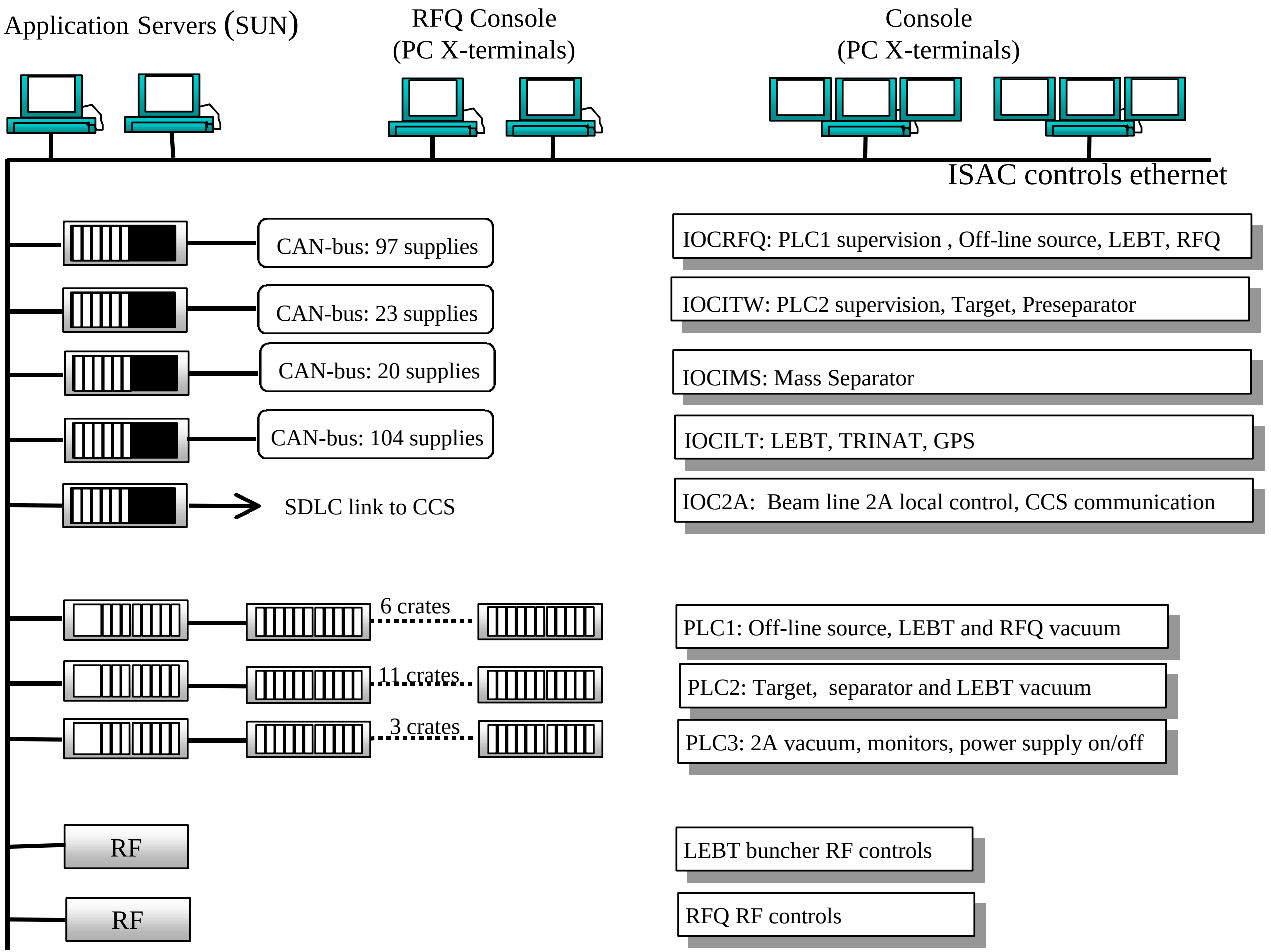


Fig. 145. ISAC control system hardware overview.

tested with the standard EPICS tool (not too satisfactory on data retrieval) and a beta version of the promising new channel archiver.

A Web-based electronic log-book program from Fermilab was installed and used during ISAC commissioning. An “alpha” version of Web-based fault reporting was implemented and connected to a PC-based database application for fault tracking.

On the level of the EPICS function block data base, CAPFAST schematics were produced for all new sub-systems. In addition, new device and component schematics were developed for the Chalk River power supplies, stepper motor driven diagnostic devices and the supervisory control of the rf systems. Component schematics were adapted to support the new TRIUMF built VME modules.

EPICS device and driver support level was written for:

- the TRIUMF designed VQSX beam current amplifier
- the TRIUMF designed 32-channel digital I/O module
- supervising the rf control systems of low energy buncher and RFQ using a combination of TCP/IP and UDP/IP protocols as required by the RF Controls group
- the TCP/IP based communication with the new Modicon PLCs.

Subroutine records were developed for:

- the high energy emittance rig at the RFQ which uses a rotating slit/harp combination
- digitizing the pulse train of the 0518 harp modules
- calibrating stepper motor driven devices.

In terms of EPICS infrastructure, the system was converted to use the latest EPICS release 3.13.0 beta10. All IOCs were upgraded to VxWorks version 5.3 which allowed the use of the Tornado virtual console.

The ladder logic PLC programs were extended to support all new vacuum systems and the surface ionization source.

Maintenance work was done on the ISAC device data base applications which generate specification and test documents.

## ISAC-II

We have been making plans for the next stage of ISAC. As presently designed, ISAC will provide radioactive ion beams up to mass 30 and energy 1.5 MeV per amu. Two workshops have been held to poll the user community, and the result is a specification of 6.5 MeV/u with mass up to 150.

With a charge-state booster (CSB), it will be possible to raise the mass to 150 while retaining the existing RFQ. However, the equilibrium charge state for stripping at the RFQ final energy of 150 keV/u is not high enough for the heavier species: for example, for mass of 100, there will be very little beam in charge states larger than 15. Since the ISAC-I DTL requires a charge-to-mass ratio of at least 1/6, this DTL cannot be used for ISAC-II.

The solution is to increase the energy after the RFQ, but before stripping. One can minimize the linac length, and therefore overall cost, by optimizing stripping energy. This is because a too-low stripping energy does not strip to a high enough charge state, while a too-high stripping energy makes the pre-stripper linac too long. The optimum stripping energy for mass up to 150 is 400 keV/u, and the median charge state is such that the lowest $q/A$ is 1/7.

A cost effective configuration to reach 400 keV/u is to continue the acceleration straight north of the RFQ MEBT line (Fig. 146). This would require an addition to the present building to widen it northward. The energy gain of 0.25 MeV/u requires a total rf voltage of $(0.25 \times 30 =)$ 7.5 MV. A DTL very similar to the ISAC-I DTL IH linac would be about 5 m long assuming an average gradient of 1.5 MV/m and could be placed downstream of the first MEBT bender after a short matching section. After the new DTL, the beam would go through a beam transport system consisting of a short matching section, stripping foil, a 90° bend for charge selection and a matching section to the post-stripper linac.

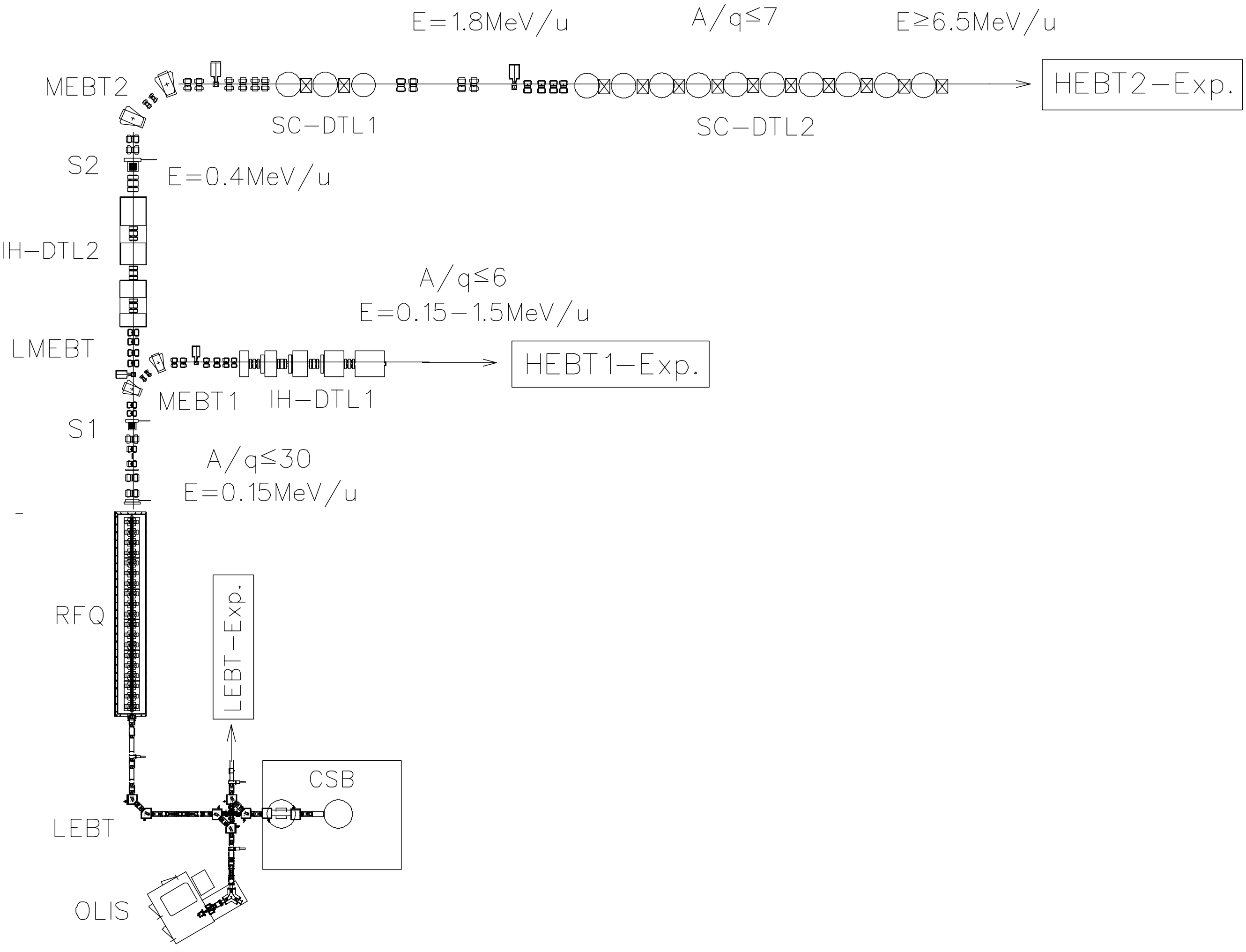


Fig. 146. ISAC-II layout.

To reach 6.5 MeV/u from 0.4 MeV/u with $A/q = 7$ requires a total voltage gain of 42.7 MV. A room temperature linac should be composed of long, many-gap modules (like the ISAC-I IH DTL), else the rf power supply and running costs become prohibitively large. Such a structure running cw would have a gradient of 2.2 MV/m and including the required focusing quadrupoles between tanks would therefore be at least 28 m in length. Higher electrical gradients are possible in principle, but in cw operation rf power dissipation in the drift tubes becomes a limiting factor. These problems disappear if we instead use superconducting cavities. In that case, an accelerating gradient of 3 MV/m is conservative (5 MV/m has been achieved).

We propose to build the linac of many short (2 to 4 cell) cavities. Short modules have the advantage that the ions do not have to rigorously follow a fixed velocity profile to stay in phase with the rf, since the modules are independently phased. This allows pushing the energy of particles with $q/A > 1/7$: for example, ~15 MeV/u can be attained for particles with $q/A = 1/3$. (Stripping at 400 keV/u can efficiently produce ions with $q/A = 1/3$ for $A \lesssim 30$.) Even for the highest masses, higher energies would be possible at a cost in intensity with the addition of an intermediate stripping station (see Fig. 147).

The superconducting linac would be similar to those running at other heavy ion labs, in particular Argonne and Legnaro, Italy.

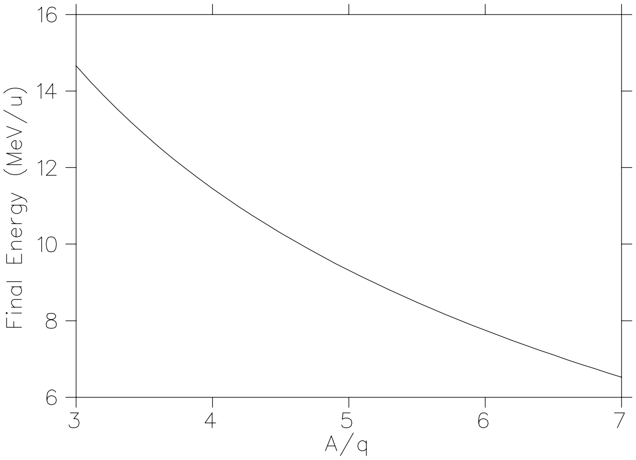


Fig. 147. Energy achievable in ISAC-II with a superconducting final stage.