PERFORMANCES OF THE ISAC HEAVY ION LINACS

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Abstract

ISAC is the TRIUMF facility for the production and post acceleration of Rare Isotope Beams (RIBs). The post acceleration section includes two normal conducting linacs, an RFQ injector and a variable energy IH-DTL, and a superconducting linac composed of five cryomodules each containing four quarter wave bulk niobium resonators. All three machines operate CW. The RFQ and DTL deliver beam since 2000 to a medium energy area with energies variable between 150 keV/u and 1.8 MeV/u. The superconducting linac, with an effective voltage of 20 MV started delivering in 2007 with performances exceeding design specifications reaching final energies up to 11 MeV/u for lighter particles. The linac gradients show no average degradation in performance. Well established operational and tuning procedures allow reliable operations. Schemes have been developed to effectively deliver the very low intensity (as low as few hundred particles per second) radioactive ion beams. The superconducting linac will be upgraded with the addition of twenty more cavities (boosting the acceleration voltage to 40 MV) by the end of 2009 making the reliability quest more challenging. In this paper we present past, present and planned operations with the ISAC linacs.

INTRODUCTION

The delivery of radioactive ion beams (RIBs) is challenging because it requires many components to perform properly at the same time. The TRIUMF facility for isotope selection and acceleration (ISAC) uses the isotope separation on line (ISOL) method [1]. ISAC has three main components: the driver, the target station and the post accelerators. This delivery chain can use also a charge state booster (CSB) to increase the charge state of the single charged ions coming from the target.

A group of physicists, with different area of expertise, is present in TRIUMF in order to maintain high standard of reliability and productivity in the beam delivery field. This group covers many aspects of the delivery beyond the basic production and post acceleration processes. In particular it relates with the experimental groups in order to facilitate the installation of the experiments itself and to adapt the best tuning strategy for each individual need. Each expert follows during the runs the performance of its own section to maximize the output of the experiment. This is done not only fine tuning each components of the delivery chain but also training and supporting the operation group on a 24/7 basis. The group evaluates the success of each experiment based on well defined metrics. This is necessary to keep track of the performances quantitatively.

In this context the ISAC post accelerators are the last component of the delivery chain. Since the beginning of operation (back in 2000) they have a dedicated expert and therefore a well established operational and tuning procedures that allow them to be quite reliable. Maintaining the reliability of the linacs is a major goal above all in view of the ISAC-II superconducting linac upgrade.

ISAC RIB PRODUCTION FACILITY

The driver of the ISAC facility is the TRIUMF cyclotron [2](see Fig. 1). The cyclotron accelerates H^- ions up to an intensity of 250 μA to a maximum energy of 500 MeV. The H^- are then stripped and protons are extracted in three different beam lines at different energies. One of these beam line is dedicated to the ISAC radioactive beam production. In this case the beam is extracted at 500 MeV and up to 100 μA. The simultaneous extraction of multiple beams with stable delivery is challenging. Nevertheless a 90% availability of the proton beam for the ISAC facility is regularly achieved.

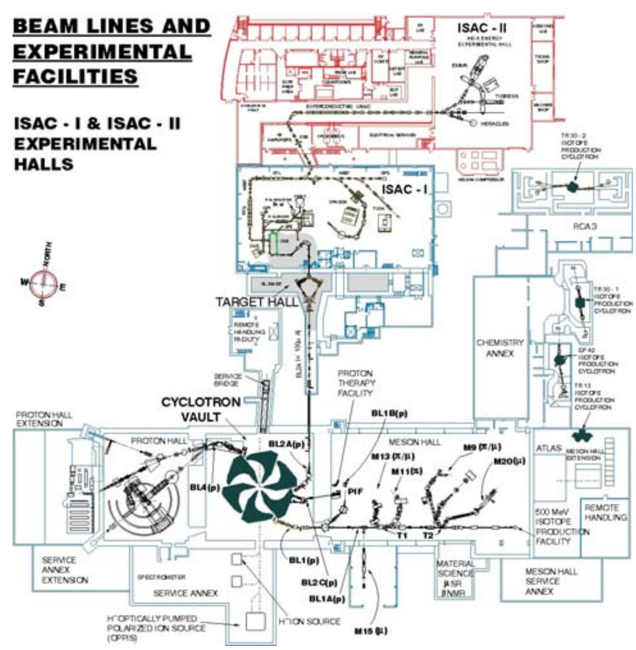

Figure 1: Overview of the TRIUMF site. The main machine is the H^- 500 MeV cyclotron used also as driver of the ISAC facility.

The ISAC facility has two independent underground target stations that can be fed with proton one at the time. This allows service on one target station while producing and delivering radioactive beams with the other. The neutral isotopes produced in the target can be ionized using different sources available at ISAC.

The ionized isotopes are then selected in the mass separator and sent to ground level where the experimental areas and the post accelerators are located. After selection it is also possible to boost the charge state of the radioactive ions by diverting them through an electron cyclotron resonance ion source (ECRIS). This charge breeder allows the post acceleration of masses A>30.

ISAC POST ACCELERATORS

The RIBs can be delivered to three experimental areas as represented in Fig. 2: a low energy area where the ions are accelerated at source potential (up to 60 kV),a medium energy area (β=1.8%→6%) or a high energy area (β=6%→15%) where the ions are post accelerated with linacs.

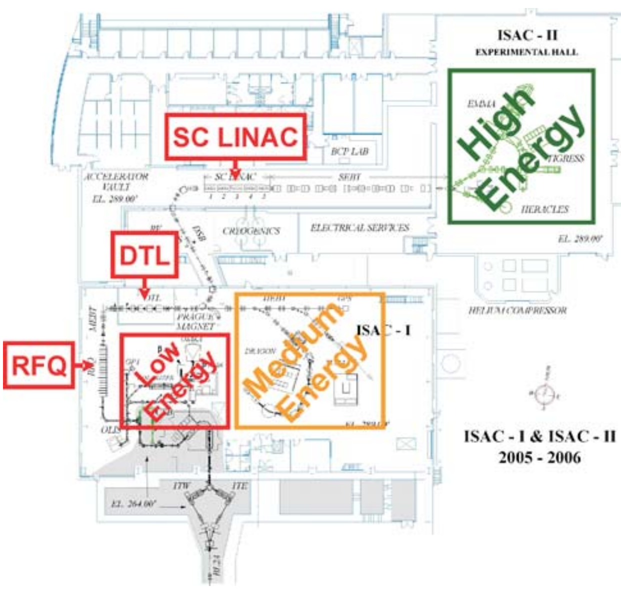

Figure 2: Overview of the ISAC facility at TRIUMF. The ISAC II linac is superconducting while in ISAC I the RFQ and the DTL are room temperature machines.

The first stage of acceleration uses a radio frequency quadrupole (RFQ, top left Fig. 3) acting as an injector [3]. The RFQ boosts the energy from 2 keV/u to 150 keV/u. It can accelerate mass to charge ratio of 3≤A/Q≤30. The RFQ is a room temperature CW machine operating at 35.36 MHz. In order to achieve a high quality output longitudinal emittance the beam is prebunched at the entrance by means of a three harmonics electric buncher, the fundamental being 11.78 MHz. Part of the beam transmitted but not accelerated is dumped into a fixed collimator installed at the exit port of the RFQ. The particles transported into the downstream medium energy beam transport (MEBT) line is 75-80% of the injected. This configuration produces an estimated longitudinal emittance after the RFQ of 0.22 π keV/u·ns [4].

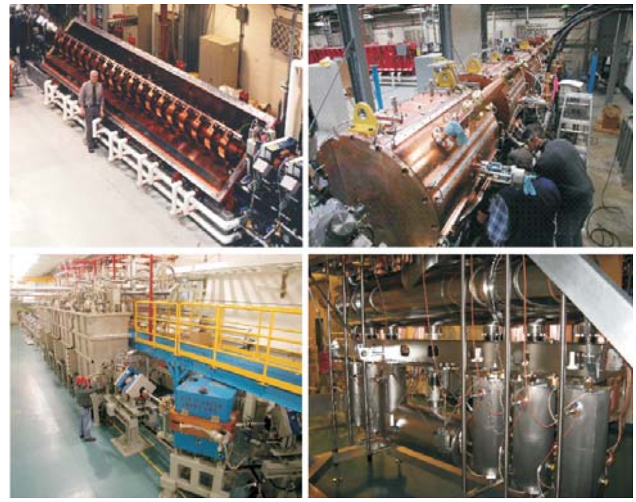

Figure 3: The ISAC accelerators: the RFQ (top left), the DTL (top right), the medium beta section of SC linac (bottom left) and the high beta section future upgrade of the SC linac (bottom right).

After the RFQ the charge state of the ions is increased by stripping through a thin carbon foil (4 μg/cm^2). As a general rule the most populated charge state is selected using magnetic benders as long as the mass to charge ratio is within 2≤A/Q≤6 set by the second stage of acceleration, the drift tube linac (DTL, top right Fig. 3). The efficiency of the stripping foil depends on the mass of the stripped ions; in most of the cases it ranges between 30% to 50%. In order to maintain a good beam quality after stripping in terms of both transverse and longitudinal emittances, the beam is focused in the transverse directions and in time at the foil location.

The DTL [5] is a variable energy machine covering the entire range of design energies 150 keV/u≤E≤1.5 MeV/u. These design boundaries are indeed overtaken pushing the limit in both directions [6] (see Fig. 4). The DTL is a separated function machine composed of five IH interdigital structure accelerating tanks and three split ring bunchers located between the first four tanks. This layout produces good beam quality for each deliverable energy. After the fourth tank the beam quality is already good enough that no buncher is required. The resonance frequency of the tanks and bunchers is 106.08 MHz. They operate at room temperature in CW mode. Transverse focus through the linac is provided by quadrupoles triplets between each tank. The transmission of this linac is greater than 95%. The DTL is also used as an injector for the ISAC II superconducting (SC) linac.

The present installation (medium beta section, bottom left Fig. 3) of the SC linac [7] is composed of five cryomodules. Each cryomodule houses four superconducting cavities and one superconducting solenoid. The superconducting cavities are bulk niobium quarter wave resonators at 106.08 MHz operating at 4K. The linac is now operating for two years at an average gradient of 35 MV/m peak

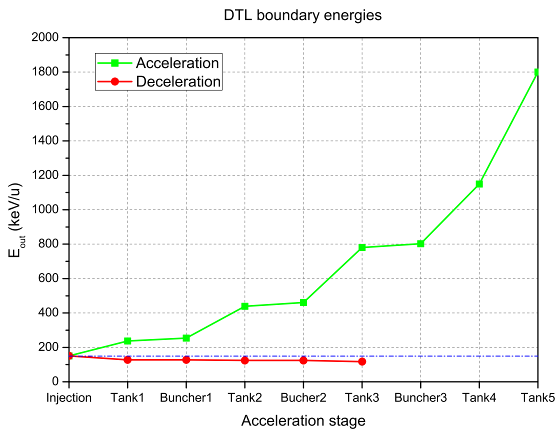

Figure 4: The boundary energies of the DTL: the design energy range is 0.15-1.5 MeV/u.

surface field (7 MV/m of acceleration) at 7W exceeding the specification of 30 MV/m at 7W. During this period there is on average no significant degradation in the cavities performance. Each cavity is independently phased at -25° synchronous phase. The transmission through the SC linac is 100%.

An upgrade (top right Fig. 3) of the SC linac is underway [8]. The upgrade (high beta section) consists of twenty more cavities housed in three cryomodules installed downstream of the existing section. The new superconducting cavities are quarter wave bulk niobium resonators operating at the higher frequency of 141.44 MHz. The first two cryomodules house six superconducting cavities and one superconducting solenoid while the last one has eight superconducting cavities and one superconducting solenoid. This upgrade increases the ISAC II linac voltage capability to 40 MV. This voltage will boost the beam energy above the Coulomb barrier for all masses. Since the SC linac always operates at the maximum possible voltage for stable operation, the final energy depends on the mass to charge ratio of the accelerated species. We anticipate an energy of 22 MeV/u for A/Q=2 and 8 MeV/u for A/Q=6. The cryomodules are scheduled for installation and commissioning by the end of 2009.

BEAM DELIVERY OPERATION

Post Accelerators Tuning

ISAC is design to produce and to post accelerate radioactive beams but we also deliver stable ion beams (SIBs). The low intensity of the radioactive beam, ranging typically between 10^3 and 10^6 particle per second, makes not possible to tune the beam lines and the accelerators. The post accelerator sections are tuned using a SIB as pilot beam with intensities of the order of enA. The stable beam used has the same mass to charge ratio of the RIB.

The stable ions are produced in an off line ion source (OLIS). OLIS is composed of three sources: a surface, a microwave and an electron cyclotron resonance (ECR) source. This last source produces multi charged isotopes that match the beams coming from the CSB.

The switchover procedure from the pilot beam to the radioactive is straightforward. The transmission of the RIB is checked using several low intensity detectors (like silicon detector, photodiode or channeltron) distributed along the beam line.

Beam Delivery Strategy

As already mention the main challenge of delivering radioactive beam is the complexity of the delivery chain. The single failure of a facility component (driver, target or accelerators) results in no particle at the user end. In order to complete successfully a scheduled experiment is essential that every components work properly.

The strategy adopted by TRIUMF to guarantee this success is to have a group of physicists (beam delivery group) experts in different section of the facility. This group of physicists is ultimately responsible to ensure high standard of reliability and productivity. These two concepts are defined quantitatively using two metrics.

The reliability is defined with the following Eq. 1 (metric1):

$$reliability = \frac{beamhoursdelivered}{beamhourspromised} \quad (1)$$

where the beam hours promised represent the availability of the system. The availability is defined as the number of hours (in a year) we commit to deliver beam to the experiments. For each experiment the availability is well defined in a pre-run meeting where all the sources of downtime (procedural time, maintenance, development, shutdown activities, extra activities...) are removed in the terms of hours from the total amount of time the experiment is scheduled to run.

The reliability lowers when a single components doesn't work. As example if the cryogenic system of the superconducting linac fails the linac goes off and the beam is not delivered. This is a source of unscheduled downtime and as consequence the reliability (in this example of the linac) goes down. The source of downtime can also be due to extra unscheduled procedural time. On the post accelerator side well defined tuning procedures allow us to schedule the right amount of time needed. One of the future goals is to increase the availability by reducing the tuning time without reducing the reliability. For the DTL we already established a new way to tune the machine that can be further developed toward a more automated tuning procedure [9]. In general we want to implement high level software application to tune the beam lines; this should increase the availability of the system.

The productivity is defined with the following Eq. 2 (metric2):

$$productivity = \frac{actualintegratedcountstouser}{promisedintegratedcounts} \quad (2)$$

where the promised integrated counts are calculated based on a minimum yield that the experiment needs in order to achieve publishable results. This minimum yield is also based on the historic yield produced for a given isotopes. This minimum has to be satisfactory both for the experiment and the beam delivery group. As far as the experiment is concerned the higher the minimum the better, while on the beam delivery side it is important to promise what is reasonably achievable. The productivity is most related to the target production. The target behavior can be influenced by many factors: the quality of the target itself, mechanical failure of the target or the target station, failure of the ionizing source.

In some way the productivity can be influenced also by the post accelerators performances with particular reference to the transmission. Considering all the linac (and the stripping foil efficiency) we typically have a transmission of 20-40% depending on the accelerated isotopes. If this transmission dropped below 20% then the productivity lowers due to poor performance of the accelerators.

The metrics used to grade an experiment success are an important resource to understand which area needs more development. The beam delivery group takes advantage of this analysis process to improve the quantity and quality of the beam delivered.

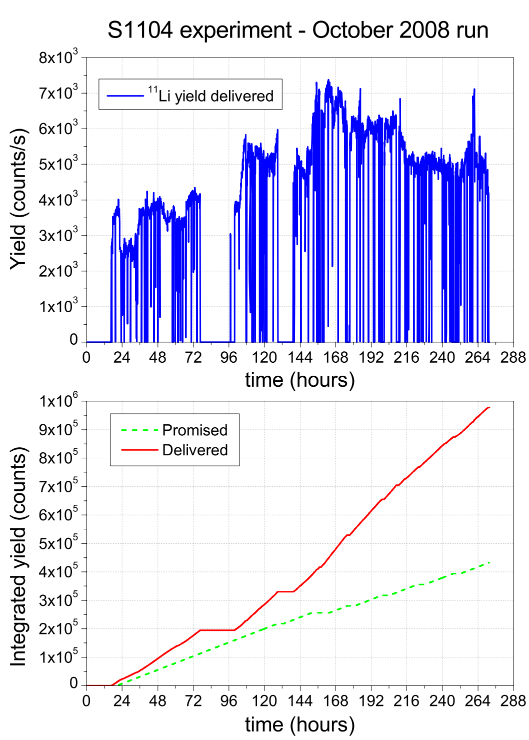

Figure 5: The top plot represents the delivered yield to the experiment S1104 in the ISAC-II experimental hall TIGRESS facility. The bottom plot represents the integrated curves of promised (green dotted line) and delivered (red line) yield.

Beam Delivery Performance

The amount of delivered beam to an experiment is recorded during each run. These data allow to calculate the reliability and productivity during the experiment. The goal is to reach a reliability higher than 75% and a productivity higher than 100%.

The top chart of Fig. 5 represents the yield of ^{11}Li delivered during experiment S1104 at the TIGRESS facility. This facility belongs to the ISAC-II experimental. The bottom chart of Fig. 5 represents integrated yield for the same experiment. The dotted green curve is the promised integrated yield while the red curve is the actual delivered one. The metrics of this experiment score a 92% reliability and a 226% productivity.

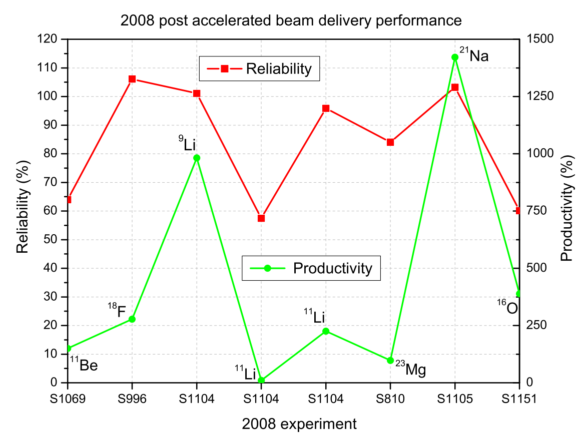

Figure 6: The plot represents the 2008 reliability (red squared line) and productivity (green circled line) curves.

The 2008 performance of post accelerated beam experiments are summarized in Fig. 6. These performance includes all the components of the delivering chain. As far as the linacs are concerned in 2008 they reach a reliability of 97%. The performance of the linacs in term of transmission has always been inside the expected values.

CONCLUSION

In order complete successfully an RIB experiment all the delivery chain components have to work properly at the same time. This makes the delivery task a challenge that at ISAC is approached with a group of physicists experts in different areas of the delivery chain. The group has two well define metrics to grade reliability and productivity of the ISAC facility. The delivery performance are collected and analyzed run by run in order to improve where necessary. In this scenario the ISAC post accelerators performed a reliability of 97%. The future goal is to maintain or to improve the reliability of the linacs and possibly increase the availability. This leads to an overall increase of beam counts at the experimental targets and therefore a potential increase in the output of the science produced.

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