A New 2.5 MeV Injector and Beam Test Facility for the Spallation Neutron Source

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Abstract. The U.S. Spallation Neutron Source (SNS) now operates with 1.2 MW of beam power on target with the near-term goal of delivering 1.4 MW and a longer-term goal of delivering > 2 MW to support a planned second target station. Presently, H^- beam pulses (50-60 mA, 1 ms, 60 Hz) from an RF-driven, Cs-enhanced, multi-cusp ion source are first accelerated to 2.5 MeV by a Radio Frequency Quadrupole (RFQ) accelerator, injected into a ~1 GeV linac, compressed to <1μs in an accumulator ring and ultimately delivered to a liquid mercury target for pulsed neutron production. In recent years concerns about the RFQ performance has motivated the procurement of a new RFQ and the creation of a Beam Test Facility (BTF) to allow off-line testing. The purpose of the BTF is to first validate performance of the new RFQ before installing it in place of the existing RFQ and later to serve as a stand-alone 2.5 MeV research accelerator employing the original SNS RFQ. After validating the new RFQ with respect to energy, emittance and transmission, the initial applications of the BTF will be to conduct 6D beam dynamic studies, develop & demonstrate ion sources capable of meeting the current and future requirements of the SNS, and contribute to neutron moderator development. This report provides a facility update, description of the BTF ion source systems as well as a discussion of the first LEBT and RFQ beam current measurements performed at the BTF.

INTRODUCTION

Oak Ridge National Laboratory operates two world-class neutron scattering facilities, the High Flux Isotope Reactor (HIFR) and the Spallation Neutron Source (SNS). The SNS is the highest power, pulsed neutron source currently operating worldwide. It supports a large research portfolio utilizing ~20 neutron instruments based around individual beamlines surrounding a single liquid Hg spallation target [1]. Intense pulses of neutrons are produced by first extracting macro-pulses of H^- ions, 1 ms in length, from an ion source with a repetition rate of 60 Hz. The baseline ion source is an RF-driven, multi-cusp, Cs-enhanced, H^- source [2] in which 50-60 kW of 2 MHz RF power is delivered to the plasma through a porcelain-enamel coated internal antenna [3]. An H^- current of 50-60 mA is typically extracted from the source with an energy of 65 kV and directed into an electrostatic Low Energy Beam Transport (LEBT) where the macro pulse is chopped into roughly 1000 mini-pulses, each <1 μs in time.

The LEBT consists of two electrostatic Einzel lenses (lens-1 and lens-2) each biased to approximately -45 kV with the second (downstream) lens being segmented into four parts to allow the application of a pulsed transverse chopping voltage of ±2.3 kV (ΔV=4.6 kV) to opposite halves of the electrode assembly and thereby directing the beam onto a chopper target electrode during the voltage pulse. The chopper target electrode is an electrically isolated, flat TZM disk with a 7.5 mm circular opening in the center which is located ~10 mm downstream of lens-2. Each lens-2 segment can also be independently biased with a DC potential of up to ±1.5 kV (ΔV_{max}=3 kV) to precisely steer the beam into the RFQ. The un-chopped beam which passes through the chopper target opening is then accelerated first to 2.5 MeV by a Radio Frequency Quadrupole (RFQ) accelerator and injected into a Medium Energy Beam Transport (MEBT) which matches the beam into the linac. The SNS linac then accelerates the beam to

~1 GeV, where it is stripped of electrons and injected into a proton storage ring. Each mini-pulse is then timed to be spatially stacked together creating a single proton pulse of ~35 A, <1 μs in time, which is delivered to the liquid Hg-target at 60 Hz [1]. The facility baseline design calls for delivering 1.4 MW of proton beam power to the target and future plans include roughly doubling that power including 500 kW to be delivered to a second long-wavelength target station [4]. This will require the ion source to produce MEBT beam currents of ~35 mA and ~50 mA, respectively [5].

Although our ion sources produce 50-60 mA of beam current measured into the SNS RFQ, not much more than ~35 mA exit the RFQ, a beam current which is sufficient for 1.4 MW neutron production but insufficient for the planned facility upgrades. A multi-year effort to systematically collect measurements of SNS RFQ transmission has shown transmissions of typically only 60-75%, significantly less than the 90% measured in 2010 [6]. PARMTEQ simulations show that 80 to 90% RFQ transmission can be expected when the structure is operated at the design field strength. Operational experience with the RFQ shows as the 402.5 MHz RF drive power is increased, thermal instabilities limit higher power operations before the transmission starts to saturate. This condition could have resulted from a field distortion which has occurred after 2010. For example, a mechanical vane shift of 10's of μm could be responsible for the current impaired operation of the RFQ [7].

In 2009 a decision was made to procure a spare RFQ as a potential replacement for the existing SNS RFQ and Research Instruments GmbH [8] was contracted to build it from the ORNL design [9]. In 2013 the spare RFQ was delivered to the SNS and work began in earnest to design and build a Beam Test Facility (BTF) to test it independent of the main SNS accelerator [5, 10, 11]. This report gives an updated status of the BTF, describes the ion source /LEBT systems and discusses the initial beam current measurements made there. The major components of the BTF are shown in Fig.1.

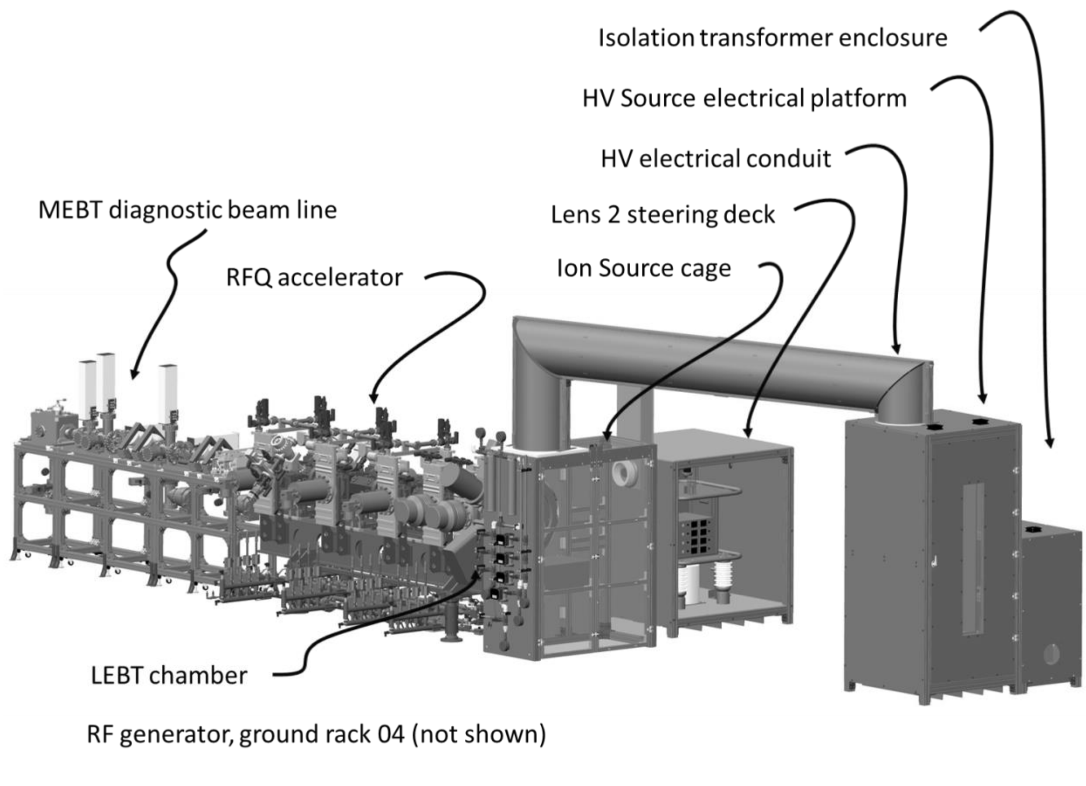

FIGURE 1. Illustration of the major components of the BTF, not shown are the AC distribution cabinets, 2 MHz solid-state 120 kW RF generator, ground LEBT power supply rack, Personnel and machine Protection system racks (PPS &MPS), 402.5MHz RFQ Klystron and Modulator, PPS controlled area fence and local computer control terminals.

THE BEAM TEST FACILITY

The BTF is required to be capable of measuring the transmission, energy and emittance of the beam through the RFQ as well as make an initial assessment of system reliability. Later the BTF will operate as a stand-alone accelerator employing the original SNS RFQ to support various research efforts. Not shown in the figure but essential to operations are the AC distribution cabinets with safety contactors, 2 MHz solid-state 120 kW RF generator, ground LEBT power supply rack, Personnel and Machine Protection System racks (PPS & MPS), 402.5MHz RFQ Klystron and Modulator, Epics-based computer control terminals and PPS controlled-access area fence. The facility utilizes many interchangeable components with the SNS systems that include: all of our H^- ion sources (internal and external antenna versions), our LEBT electrode structures, most individual ion source and LEBT power supplies and the RFQ accelerator itself. Since the BTF is not required to generate chopped beams, the LEBT chopping power supplies and associated cabling employed on the SNS were not installed on the BTF.

Like the SNS, the BTF ion source and some of the associated power supplies are operated at -65 kV and the two LEBT electrostatic lenses operate near -45 kV while the rest of the BTF is at or near ground potential. High voltage electrical platforms are therefore required to house some of the associated ion source power supplies (HV-source platform) as well as the DC lens-2 steering supplies (steering deck), both are shown in Fig.1. The BTF HV-source platform, shown in Fig. 2, is more compact than the SNS HV-source platform housing all necessary power supplies and control hardware within an electrically isolated, single 19 inch x 20U equipment rack. The corona shielded rack is supported by 4x100 kV insulators, all HV gaps are greater than 6 inches and power is supplied by a ~20 kVA, 75 kV 3-phase enclosed isolation transformer shown in Fig. 1. Cabling from this platform is connected to the ion source cage through a HV isolated conduit. The ion source cage provides protection from the source HV and is similar to the SNS source cage with the exception that the 2 MHz matching and isolation networks have been directly integrated into the structure as shown in Fig. 3.

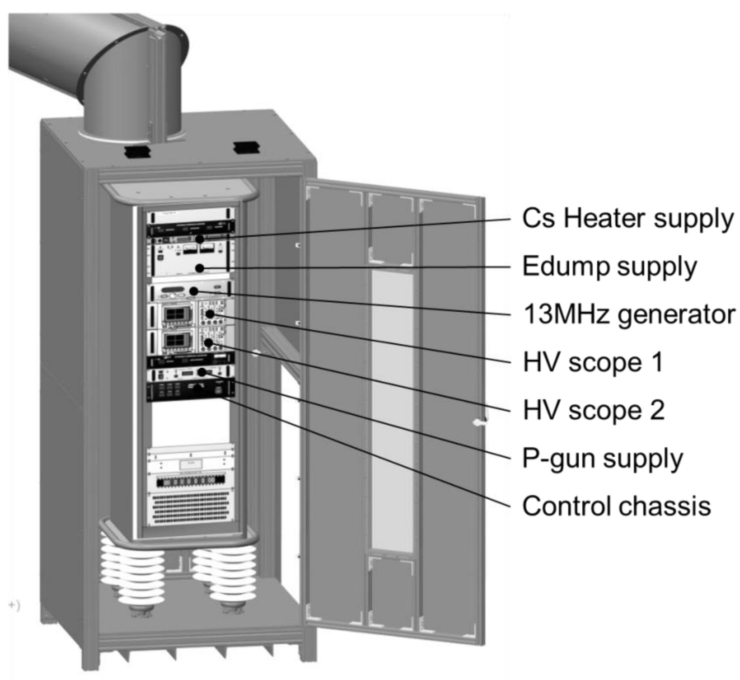

FIGURE 2. Illustration of the BTF HV-source platform which contains scopes to monitor the 2 and 13 MHz systems as well as the electron dump. It also contains the source 13MHz, electron dump, plasma gun and Cs heater power supplies.

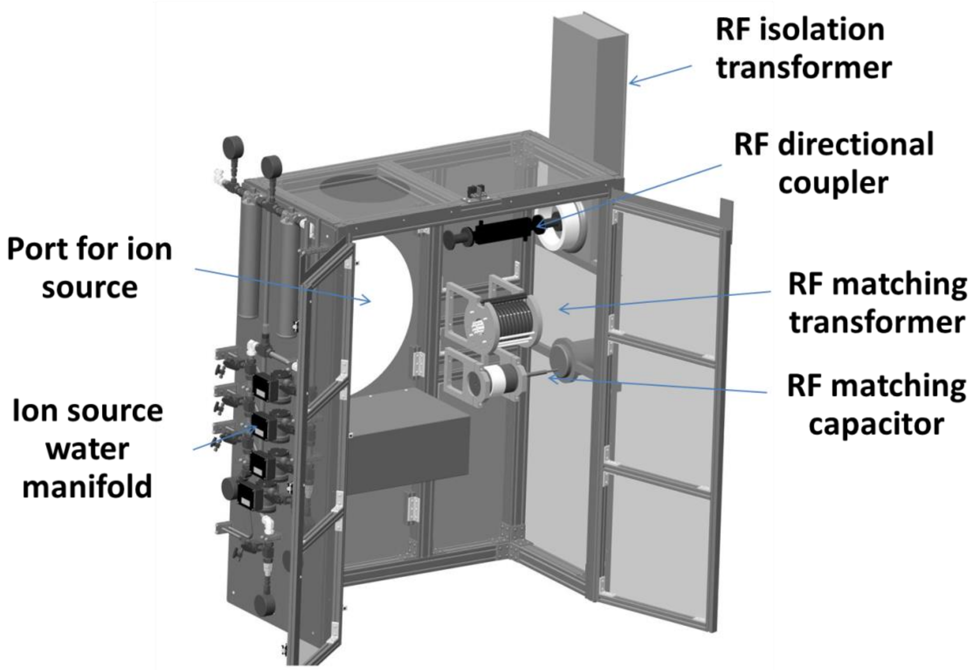

FIGURE 3. Illustration of the ion source enclosure showing the integrated RF ion source components. RF power from the 2 MHz generator enters the source cage through an RF isolation transformer and is then coupled directly to the impedance matching transformer which is, in turn, coupled to the ion source antenna

Figure 4 shows the steering deck which contains four -3kV DC steering supplies which can apply differential transverse voltage to the individual lens-2 segments to provide beam steering into the RFQ.

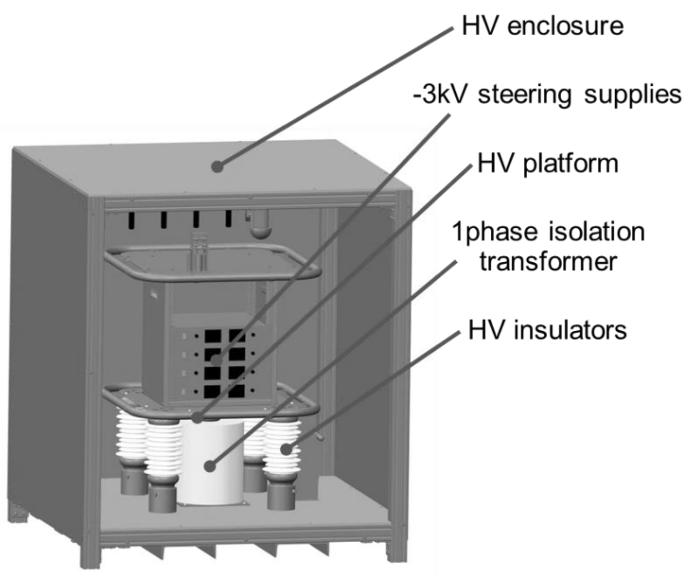

FIGURE 4. Illustration of the BTF steering deck showing the steering supplies, single phase isolation transformer and HV insulators.

The new 2.5 MeV RFQ was manufactured by Research Instruments and delivered to ORNL in November 2013 [8]. It features a 4-vane accelerating structure, mechanically robust octagonal cross section with a total length of 3.7 m constructed from 4 longitudinal sections. The RFQ operates with ~600 kW of pulsed 402.5 MHz RF power with ~10% duty factor and has the ability to accelerate up to 60 mA of H^- current. The beam dynamics of the accelerator and the mechanical LEBT/MEBT interface flanges are the same as employed in the SNS production RFQ. The new RFQ differs from the original by having considerably more pumping speed (4 x 1700 l/s turbo molecular pumps, 6 x 2500 l/s cryogenic pumps) as well as a more massive, single-material, solid copper structure which should be more resistant to deformation [9].

The BTF MEBT is designed to transport the beam without losses to a 6 kW beam dump while allowing a suite of diagnostics to interrogate the beam. Six quadrupole focusing magnets and 2 magnetic correctors accomplish beam transport with no provision for longitudinal bunch focusing yet being incorporated. The MEBT beam diagnostics suite includes: beam current transformers at the entrance and exit of the MEBT; 2 pair of slits separated by 1 m which allow simultaneous transverse emittance measurements in 4D (x,x',y,y'); a movable beam position and phase monitor capable of time-of-flight beam energy measurements; a fast Faraday cup for longitudinal bunch profile and phase measurements and an energy resolving dipole magnet and associated diagnostics. In total simultaneous 6D (x,x',y,y',E,ϕ) beam measurements should be possible [10,11].

Presently, the BTF is operational and beam operation underway. Here is a timeline of the major milestones of the project:

- July 2009: began writing equipment specifications for new RFQ
- March 2011: final RFQ design reviews and manufacture at RI begins
- July 2013: Ion Source/LEBT systems design and acquisition work begins in earnest
- Nov 2013: RFQ delivered to ORNL & assembly
- August 2014: installed 1^{st} ion source (baseline #6)
- July 2015: RFQ fully conditioned to 1ms, 60Hz, 550kW with no beam
- Aug 2015: 1st plasma and 1st HV-platform operation
- March 2016: 1st beam in LEBT, RFQ is off
- April 2016: 1st LEBT beam current measurements using pulsed deflection supply
- August 2016: BTF operational readiness review
- Sept 2016: DOE authorization to operate & 1^{st} accelerated beam at the BTF
- Sept 2016: Initial beam current measurements

The future timeline includes:

- Fall 2016 High accuracy measurement of energy, emittance & transmission; high power beam tests
- Jan 2017 decision to perform RFQ swap BTF RFQ to SNS: shut down BTF and begin transfer
- March 2017 install BTF RFQ on SNS during long Spring outage
- Aug 2017 install Berkeley RFQ in BTF

LEBT & MEBT BEAM CURRENT MEAUREMENTS

Since 2012 LEBT beam currents are routinely measured on the SNS in spite of the fact that the LEBT lacks dedicated beam current measuring devices like a Beam Current Monitor (BCM) or Faraday cup [2, 6]. This is accomplished by fully deflecting the beam passing through the segmented lens-2 electrode onto the chopper target using the transverse, pulsed chopping voltage combined with the DC steering potential. The chopper target is electrically isolated and drained through an external 50 Ω resistor where the current measurements are made. Secondary electrons from ion impact on the chopper target are suppressed by the -45 kV potential of nearby lens-2. A total transverse voltage of ΔV=6-7 kV usually required to fully dump the beam onto the chopper target [6].

Since the BTF also lacks LEBT beam current measuring devices as well as the pulsed chopping power supplies, a dedicated pulsed ΔV=6 kV supply is needed to fully dump the beam current onto the BTF chopper target. The resulting pulsed power supply, designed and developed at ORNL, is capable of generating four synchronous outputs variable up to +6 kV (one to each lens-2 segment) at 1-10 Hz with a pulse width of 1-10 µs, which can be triggered at any point in time within the source pulse [12]. When combined with the DC steering, up to 9 kV of transverse voltage can be applied across lens-2. During these studies the LEBT beam current is sampled for 5 µs shifted by 300 µs after the start of the 1000 µs source-pulse at 10 Hz. The source was operated at 60 Hz for all these measurements. The LEBT beam current can be sampled continuously during beam operations since only 5µs of the 1000 µs long pulse are removed from every 6th pulse produced by the source.

Figure 5 shows the time profile of the deflector trigger pulse and the deflected beam current from baseline source #6 incident on the chopper target under nominal source conditions: 2 MHz power: ~60 kW; H_2 flow: 29 SCCM and LEBT voltage settings (electron dump, extractor, lens-1, lens-2): 6.2, 0, 49 and 47 kV respectively. All other source parameters were held to their nominal values [5]. Here a deflection voltage of 6kV from the pulser plus 2kV of steering voltage was employed. Figure 6 shows the deflected beam current incident on the chopper target as a function of the total deflection voltage (DC steering plus pulsed deflection voltage) for the above stated source parameters. In this case, we can see that approximately 8 kV is required to deflect the full 60 mA from the source onto the chopper target. Delivery of ~60 mA of LEBT beam current was demonstrated for approximately a week of continuous operation as shown in Fig 7.

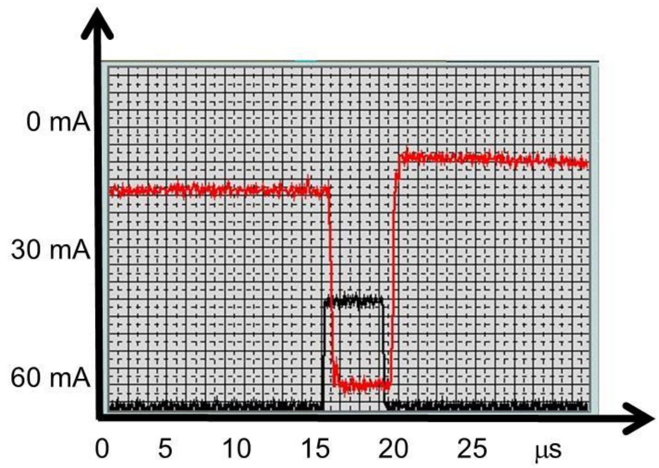

FIGURE 5. The time profile of the deflector power supply trigger voltage pulse (lower trace) and the resulting LEBT beam current incident on the chopper target (upper trace), measured in mA of current flow through a 50 Ω resistor.

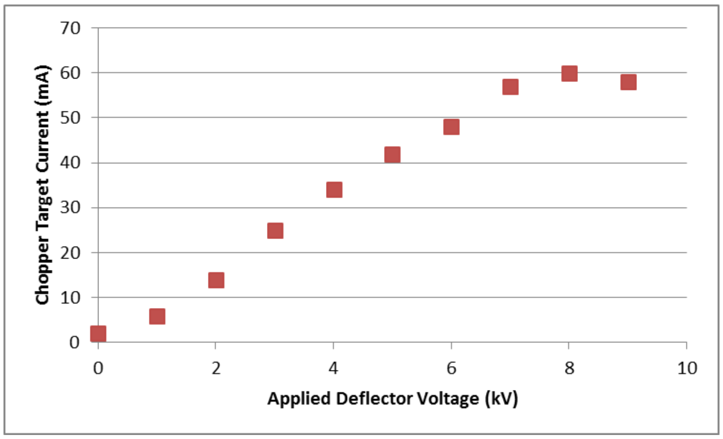

FIGURE 6. The deflected LEBT beam current incident on the chopper target electrode as a function of total transverse deflection potential (pulsed voltage plus DC steering potential).

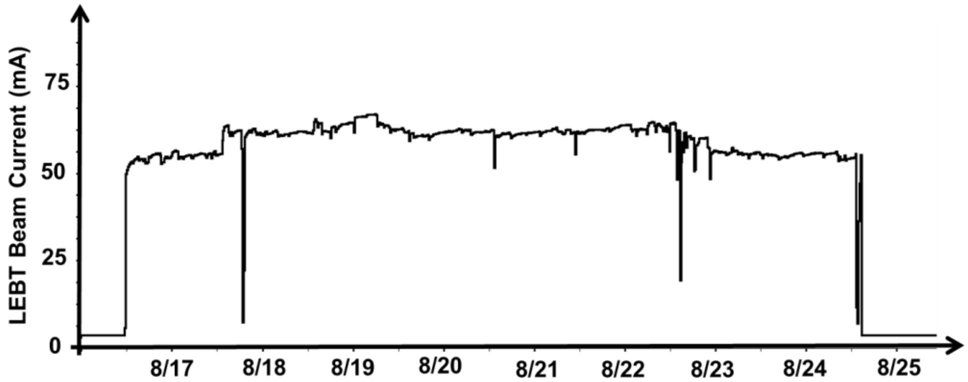

FIGURE 7. The archived record of the BTF LEBT beam current in mA running for >1 weeks of continuous operation.

Since September 2016 beam from baseline source #6 has been accelerated through the RFQ on the BTF. RFQ transmission measurements are made by simultaneously measuring LEBT and MEBT beam currents and reporting the ratio of these values. The MEBT beam current was measured by Beam Current Monitors (BCMs) located at the entrance and exit of the MEBT. It was found that after careful MEBT tuning both these BCMs gave the same results indicating close to the expected 100% MEBT transmission.

Initially the RFQ transmission was measured with LEBT beam currents of around ~20 mA. A typical measurement here would be: 24 mA of LEBT current, 22 mA of MEBT current yielding and RFQ transmission of ~91%. System parameters during this test were: source RF power: ~35 kW; H_2 flow: 30 SCCM; LEBT settings (electron dump, extractor, lens-1, lens-2): 6.2, 0, 46 and 53 kV respectively; RFQ power reference amplitude: 0.35 (arbitrary units). Later the LEBT current were increased to ~45 mA in which a MEBT beam current of 39 mA was observed yielding an RFQ transmission of ~87%. System parameters here were: source RF power: ~50 kW; H_2 flow: 30 SCCM; LEBT settings (electron dump, extractor, lens-1, lens-2): 6.2, 0, 45 and 42 kV respectively; RFQ reference amplitude: 0.35. The maximum current delivered to the MEBT beam stop at 2.5 MeV was 50 mA which was achieved using 2 MHz RF power: ~70kW; H_2 flow: 30 SCCM; LEBT settings (electron dump, extractor, lens-1, lens-2): 6.2, 5, 47 and 43 kV; RFQ reference amplitude: 0.36. Unfortunately, the chopper target feedthrough electrical connection failed so we were not yet able to produce detailed transmission versus beam current plots.

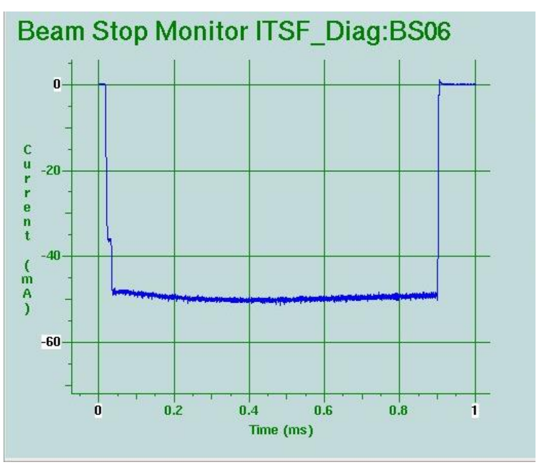

FIGURE 8. MEBT BCM beam current measurement showing 50 mA of 2.5 MeV H^- beam on the BTF.

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