COMMISSIONING OF THE SPALLATION NEUTRON SOURCE FRONT END SYSTEMS*

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Abstract

The Front-End (FE) for the Spallation Neutron Source (SNS) accelerator system is a 2.5-MeV linac injector consisting of the following major subsystems, the rf-driven H- ion source, the electrostatic Low Energy Beam Transport line, a 402.5 MHz RFQ, the Medium Energy Beam Transport line, a beam chopper system and a suite of diagnostic devices. After construction and initial commissioning at LBNL the Front End was shipped to Oak Ridge in the summer of 2002, installed at the SNS site and re-commissioned. This paper provides an overview of the major design features and the experimental results obtained during the final commissioning of the Front End Systems. Performance of the various subsystems will be described, and the final beam output performance will be summarized.

INTRODUCTION

The SNS accelerator systems are comprehensively discussed elsewhere [1]. They are designed to deliver intense proton beam pulses to the spallation target at 60Hz repetition frequency with average beam power of 1.44MW.

The front-end for the SNS accelerator systems is a 2.5MeV injector consisting of the following major subsystems: the rf-driven H- source, the electrostatic low energy beam transport line (LEBT), a 402.5MHz RFQ, the medium energy beam transport line (MEBT), a beam chopper system and a suite of diagnostic devices [2,7]. The beam line is shown schematically in Fig.1. The front-end is required to produce a 38mA beam of 2.5MeV energy at 6% duty factor. The 1ms long H- macro-pulses are chopped at the revolution frequency of the accumulator ring into mini-pulses of 645ns duration with 300ns gaps. Beam chopping is performed by two separate chopper systems located in the LEBT and MEBT, respectively. The LEBT chopper removes most of the beam charge during the mini-pulse gaps, and the MEBT chopper further cleans the gap and reduces the rise and fall time of the mini-pulse to 10ns. The main design parameters for the SNS front-end are listed in Table 1. After construction and initial commissioning at LBNL [3] the front-end systems were shipped to Oak Ridge in the summer of 2002, installed at the SNS site (Fig. 2) and re-commissioned. In spite of the fact the required beam parameters were achieved during commissioning of the front-end at Berkeley, an extensive re-commissioning program was carried out to prepare the front-end for delivering beam to the linac at its permanent location. A commissioning period of two months was allocated, limited by installation activities. As a result, the main commissioning goals were achieved at a reduced duty factor of ~.1% after 46 days of intense work.

Table 1. Parameters of the SNS front-end system

Output beam energy	2.5 MeV
Peak current	38mA
Transverse emittance (norm.)	<.3 π mm mrad
Longitudinal emittance	< .15 MeV degree
Pulse width	1ms
Repetition rate	60Hz
Chopping frequency	1MHz
Chopping extinction ratio	$< 10^{-4}$

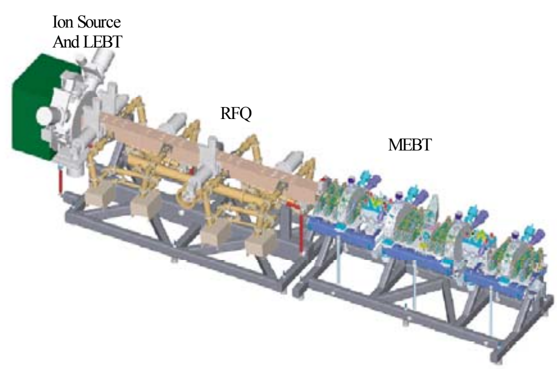

Figure 1. Schematic view of the SNS front-end systems

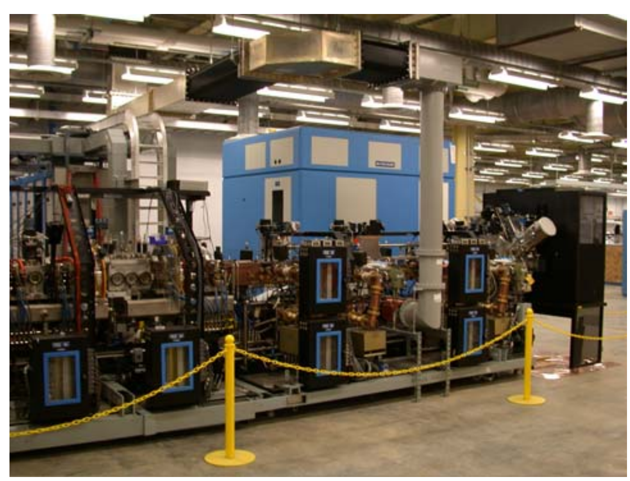

Figure 2. Front-end systems at the SNS site

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ION SOURCE AND LEBT PERFORMANCE

Details of the ion source and LEBT design can be found in [4]. General performance of the ion source during commissioning is summarized in Fig.3, where operational current is shown for each day of commissioning. Since there is no beam diagnostics in the ion source or LEBT, the beam current is measured in the MEBT after the RFQ. A maximum current of 51mA was achieved in last days of commissioning, significantly exceeding the base line requirement of 38mA. Continuous 24/7 operation of the ion source revealed several mechanical weaknesses in the LEBT design. These issues together with the remediation plan are described in [5].

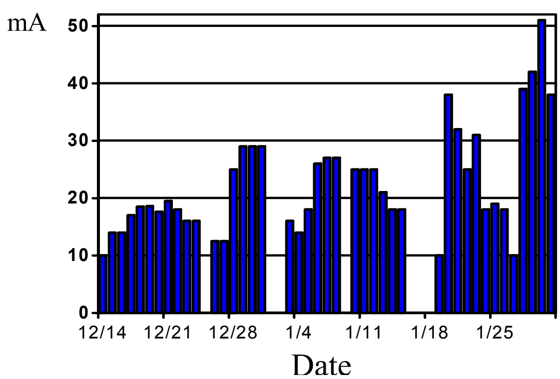

Figure 3. Beam current at the MEBT exit for each commissioning day

RFQ PERFORMANCE

The design of the 3.72-m long 4-vane RFQ with π-mode stabilizers is described in detail elsewhere [6]. It operates at 402.5MHz and accelerates H- beam from 65kV to 2.5MeV.

The RFQ was conditioned to full nominal RF gradient at 6% duty factor, and the field flatness is within ±1% peak.

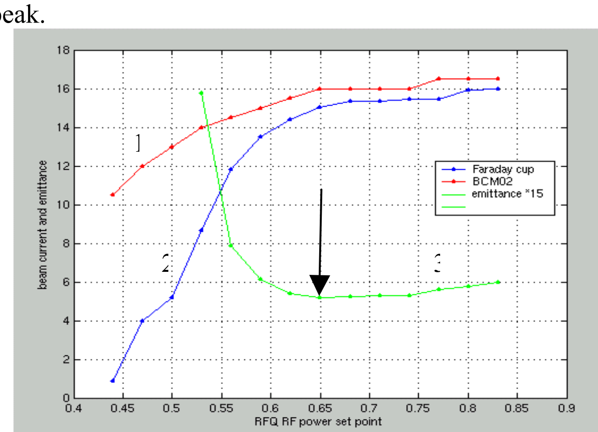

Figure 4. Beam current at the RFQ exit (1), beam current at MEBT exit (2) and transverse emittance at MEBT exit (3) vs. RFQ field. The correct set point is indicated by the arrow.

The only tunable parameter for RFQ is RF power. We used measurements of the RFQ transmission vs. RF power in order to establish the nominal set point. Since we couldn't measure the beam current injected into the RFQ from the LEBT, the absolute value of the RFQ transmission couldn't be calculated. Instead we compared measured data with PARMTEQ simulations and derived the set point and actual transmission from the model. The correct choice of RF power set point was later confirmed by transverse emittance measurement at the MEBT exit. The transverse emittance reaches a minimum when RF power is set in accordance with the transmission scan as shown in Fig. 4.

MEBT PERFORMANCE

The MEBT is a complex beam transport line [7] shown schematically in Fig. 5. It matches the beam from the RFQ through the MEBT chopper system and into the drift-tube linac. Fourteen quadrupole magnets and four rebuncher cavities provide transverse and longitudinal focusing. The MEBT is equipped with a suite of beam diagnostics including two beam current monitors (BCM), six beam position and phase monitors (BPM) installed within quadrupole magnets, five dual- plane wire scanners (WS) and slit/collector-type emittance device at the MEBT exit. Detailed description of the diagnostics is given in [2].

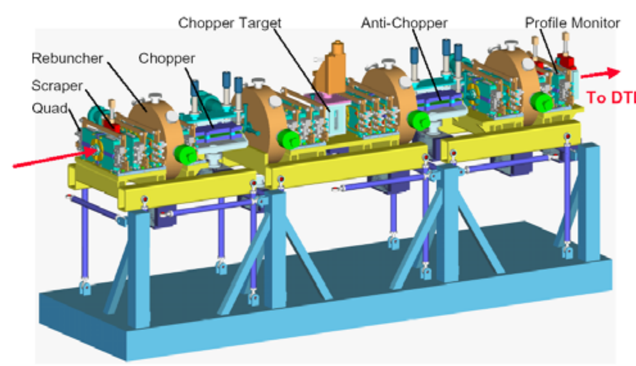

Figure 5. MEBT schematic layout

Transmission through the MEBT

The beam trajectory had to be corrected using dipole correctors in order to establish optimal transmission through the MEBT. After correction beam losses in the MEBT are below the measurement accuracy of the BCMs as illustrated by Fig. 6. In this picture beam current pulse at the MEBT exit is shown on top of the beam pulse at the MEBT entrance. The only visible beam losses are on the trailing edge of the pulse where the RF field in the RFQ decays to below nominal value and a low energy tail develops in the beam energy distribution. Low energy particles are able to reach the first BCM but are lost in the MEBT before reaching the second BCM.

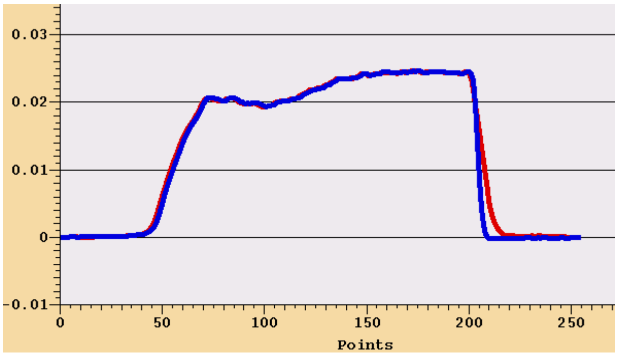

Figure 6. Snapshot of the BCM screen. Beam current pulse at MEBT exit (blue) on top of beam current pulse at MEBT entrance (red), for a 75 µsec pulse.

Transverse emittance

A slit/collector type emittance device was installed at the MEBT exit for transverse emittance measurements. It allowed measurements in one plane (vertical or horizontal). In order to switch to another plane vacuum had to be broken and the device physically rotated, therefore no simultaneous measurements in both directions were obtained. Typical emittance scan plots are shown in Figs. 7, 8.

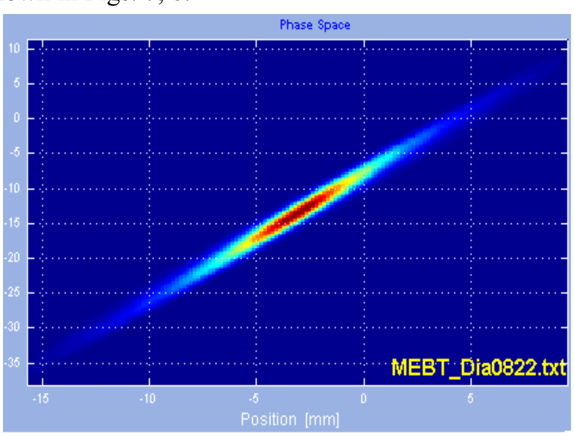

Figure 7. Vertical emittance scan. The normalized emittance ε = .3 π mm·mrad at I = 38mA.

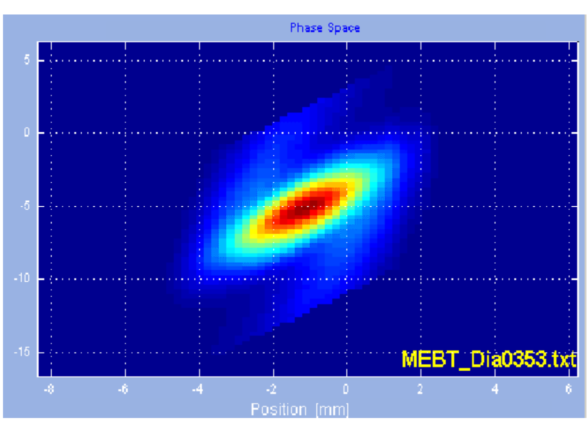

Figure 8. Horizontal emittance scan. The normalized emittance ε = .24 π mm·mrad at I = 32mA.

The horizontal emittance scan in Fig. 8 clearly shows S-shape distortion caused by non-linear space charge forces and non-linear transverse focusing in the rebuncher cavities. Even in the presence of the emittance growth due to non-linearity, the r.m.s. emittance values satisfy the requirements in a wide range of beam currents as illustrated in Fig.9, where output r.m.s. emittance is plotted vs. beam current. Figure 10 shows the dependence of the r.m.s. emittance on beam current within one pulse. Both plots demonstrate the weak dependence of output emittance upon beam current.

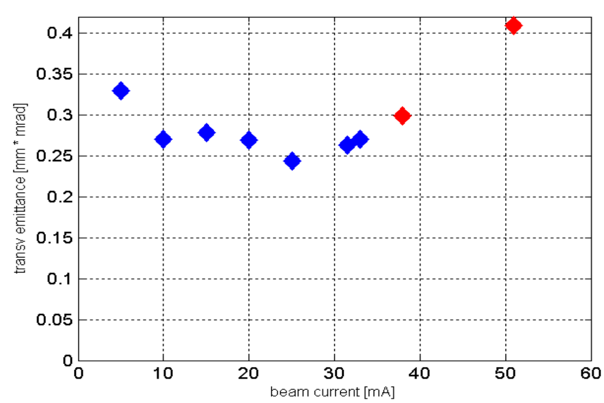

Figure 9. Transverse r.m.s. emittance vs. beam current.

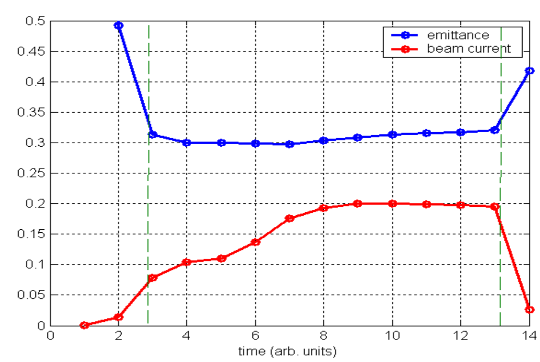

Figure 10. Transverse r.m.s. emittance (upper trace) and peak beam current (lower trace) vs. time within one beam pulse.

Transverse beam envelope

The transverse beam dynamics were compared with model predictions as illustrated in Fig. 10, where the r.m.s beam size measured using wire scanners is compared with PARMILA simulations. Measured profiles agree with simulations within 5%, limited by the accuracy of the wire scanners.

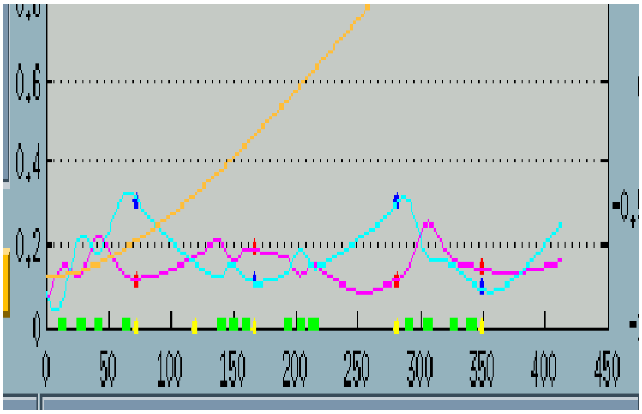

Figure 11. Transverse beam envelope (solid curves) calculated using PARMILA simulation and beam size measured with wire scanners (dots)

CHOPPING

The 1ms long H- macro-pulses have to be chopped at the revolution frequency of the accumulator ring into mini-pulses of 645ns duration with 300ns gaps. Beam chopping is performed by two separate chopper systems located in the LEBT and MEBT, respectively. The LEBT chopper removes most of the beam charge during the mini-pulse gaps, and the MEBT chopper further cleans the gap and reduces rise and fall time of the mini-pulse to 10ns.

LEBT chopper

The last lens in the LEBT is split into four quadrants to allow for electrostatic chopping using the RFQ entrance flange as a chopper target. The lens segments are pulsed with bipolar signals up to ±3kV supplied by commercial solid state active switches. Chopped beam pattern measured at the MEBT beam dump is shown in Fig. 12.

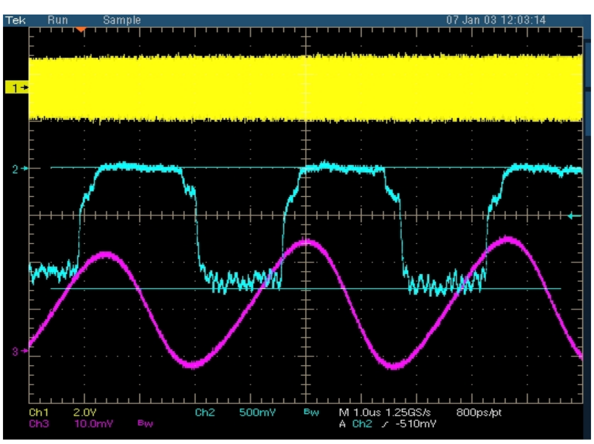

Figure 12. Oscilloscope snapshot of the beam current modulated by the LEBT chopper (meander trace).

The measured beam extinction ratio after the LEBT chopper is below the design specification of 1% at the nominal chopper voltage of 3kV. The dependence of the extinction ratio upon LEBT chopper voltage is shown in Fig. 13.

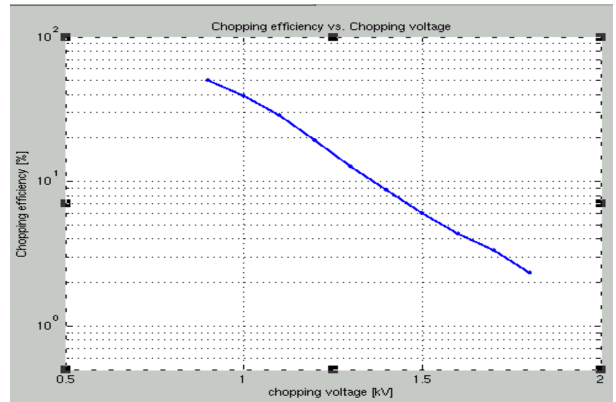

Figure 13. Beam extinction ratio after the LEBT chopper vs. chopper voltage

MEBT chopper

The LEBT chopper system is complemented by a traveling-wave chopper in the MEBT that provides faster rise and fall times to 10ns and further attenuates the beam in the gap to a level of 10-4 [7]. We were unable to test the MEBT chopper with beam due to a failure of the commercial high voltage switches feeding the chopper deflector. Nevertheless, a laser based system capable of measuring rise/fall time with 5ns resolution and beam extinction ratio with 10-4 resolution was installed and tested. Details can be found in [8].

LONGITUDINAL MEASUREMENTS

There are no baseline diagnostics for direct measurements of longitudinal parameters of the beam within a micro-bunch. The only measurements of micro-pulse temporal profile could be carried out 2m downstream of the MEBT using an experimental wide bandwidth Faraday cup [2]. With nominal settings of the rebuncher cavities in the MEBT, the beam would be completely debunched after 2m drift, therefore longitudinal focusing was retuned to achieve a minimum micro-bunch length at the Faraday cup. The measured temporal profile is shown in Fig.14.

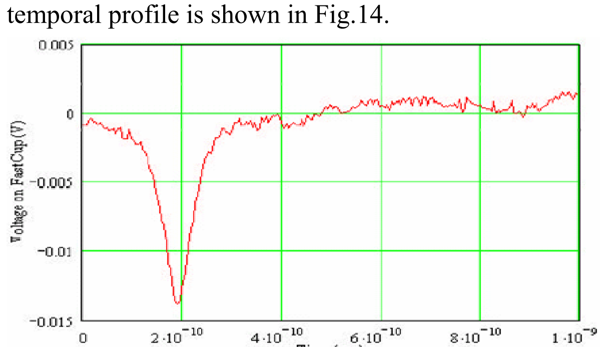

Figure 14. Oscilloscope snapshot of a temporal micro-bunch profile.

An upper limit for longitudinal emittance can be obtained from the minimum micro-bunch length using the following estimation:

$$\varepsilon \le \frac{d \cdot D}{L},$$

where d is bunch length at the waist, D is the bunch length at the focusing element, L is the distance from the focusing element to the waist. The bunch length D in the last rebuncher cavity is unknown, but as the bunch has to be in the linear part of the bunching field, we can use an estimate of $D \le \lambda/4$, where λ is wavelength of the bunching RF. This rough estimate gives an upper limit of .25 MeV·degree for the longitudinal emittance at the MEBT exit, which is twice larger than the design value. More precise measurements will be done after the DTL linac where longitudinal diagnostics are available.

HIGH POWER BEAM TEST

The final commissioning task was to reach the nominal beam duty factor of 6%, which corresponds to a 1ms pulse width at 60Hz. Pulse width of 1ms at the MEBT exit is shown in Fig. 15. At 10Hz repetition rate, the high voltage converter modulator failed and due to along repair time, the high power test was terminated. It should be noted that full power operation was demonstrated during initial commissioning at Berkeley.

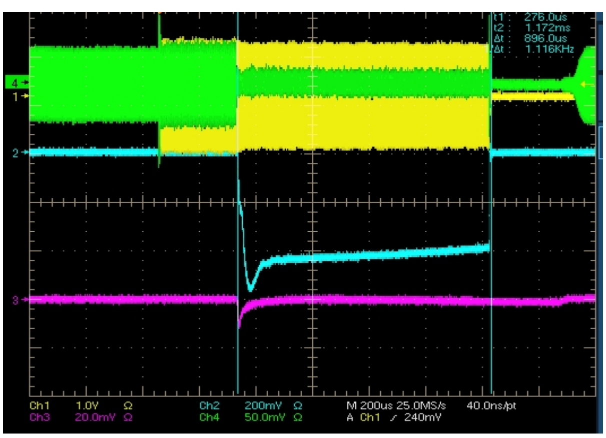

Figure 15. Oscilloscope snapshot of 1ms pulse width at the MEBT beam stop.

CONCLUSION

The FES was shipped to Oak Ridge and installed at the SNS site in the summer of 2002. Extensive re-commissioning at ORNL was performed in a two-month period ending January 31, 2003. A number of technical systems were new to the ORNL FES installation, namely the high-power RF, low-level RF and controls systems, and therefore were commissioned for the first time at ORNL. The Front-end re-commissioning was an important milestone for the SNS project as it demonstrates the first accelerated beam on the SNS site and also marks the beginning of the 2 ½ year phased commissioning program of the accelerator systems.

The primary beam parameter goals of peak current and transverse emittance were both achieved. The maximum beam current achieved at the MEBT output was 51 mA , far exceeding the design specification of 38 mA. Transverse normalized emittances at the MEBT output, measured in a variety of beam conditions, were less than the baseline specification of 0.3 π mm-mrad. The design extinction ratio of the LEBT chopper of 1% was demonstrated, as shown in Fig. 4. The MEBT chopper system, designed to achieve an extinction ratio of 10^{-4}, was not tested due to hardware difficulties.

The main beam parameter goals were achieved at reduced duty factor, typically 0.05-0.1%, limited administratively by hardware concerns. A maximum duty factor of 0.5% was achieved with full 1 msec pulse length but reduced repetition rate. The nominal 6% repetition rate was achieved during the FES commissioning at LBNL.

In addition, two novel diagnostic systems were successfully tested. A laser-based diagnostic capable of performing both transverse profile measurements and Beam-In-Gap measurements was successfully deployed and tested. A dynamic range of 10^4 in beam intensity was measured. Additionally, a prototype Fast Faraday Cup was tested and used to measure a bunch length of 140 psec at the MEBT output.

Following the completion of Front-End commissioning, two of the six Drift Tube Linac tanks will be installed in spring 2003, with commissioning studies of the Front-End and the first DTL tank beginning in the summer of 2003.

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