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ISIS INJECTOR LINAC EMITTANCE MEASUREMENT AND PHASE-SPACE TOMOGRAPHY

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Abstract

Accurate beam emittance measurement is vital for optimizing high-intensity proton accelerators. Traditional methods often only approximate the phase space ellipse linearly, limiting their effectiveness. Comprehensive analysis of phase space distribution, including nonlinearities, is essential for better characterization. This study focuses on the ISIS neutron spallation source, which is being upgraded to increase beam intensity to 300 microamps while minimizing losses. We present tomographic reconstruction and quadrupole scan results for emittance measurement at the end of the ISIS injector, showing strong alignment between measurements and simulations.

INTRODUCTION

The ISIS neutron spallation source, a pulsed high-power proton accelerator, generates high-intensity neutron radiation for various applications [1]. It includes a 70 MeV injector linac and an 800 MeV rapid cycling synchrotron (RCS) [2]. A key goal for ISIS, like other high-intensity hadron accelerators, is to minimize beam loss and radiation activation while increasing beam power and stability. Achieving this requires advanced diagnostics, precise beam measurement techniques, and an accurate beam dynamics model to optimize performance.

The High Energy Drift Section (HEDS), positioned after the injector linac, hosts diagnostics and magnets essential for beam characterization before RCS injection [3]. Accurate emittance and Twiss parameter characterization at the injector linac's end is crucial, with the HEDS setup offering robust capabilities for these measurements through both traditional and innovative methods.

Widely used measurement techniques include three-screen and quadrupole scans, with tomographic phase space reconstruction becoming increasingly valuable for analysing nonlinearities in beam phase space [4]. Algorithms like Filtered Back Projection (FBP), Algebraic Reconstruction Technique (ART), and Maximum Entropy (MENT) facilitate phase space reconstruction from one-dimensional beam profiles [5]. The MENT algorithm stands out for its efficiency with fewer beam profile measurements, addressing challenges related to beam loss and magnet strength. In Computational Tomography (CT), one-dimensional beam profiles are converted into two-dimensional phase space distributions [6].

This paper details the experimental setup at ISIS, including the quadrupole scan, three-screen monitor, and MENT-based CT method, and presents preliminary emittance measurements and phase space reconstruction results at the injector's output within the first diagnostics setup of the HEDS section.

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EXPERIMENTAL SETUP

The ISIS linac, operating at 202.5 MHz, includes a Penning ion source delivering a 45-mA output, followed by a Low Energy Beam Transport (LEBT) section with 75% transmission efficiency, achieved through three solenoids for matching to the RFQ. The RFQ raises the beam energy to 0.665 MeV with over 97% transmission. The beam then enters a drift section, lacking matching before being transferred directly to the Drift Tube Linac (DTL), where four tanks accelerate it to 70.5 MeV. Due to the absence of an MEBT (under development for machine upgrade), significant beam loss occurs in the first DTL tank, resulting in 75% and 100% transmission in the first and last three DTL tanks, respectively. However, the beam's low energy prevents activation in this section. Approximately 22.5 mA of the beam is transmitted through the DTL tanks and injected into the RCS synchrotron. Fig. 1. shows the schematic of the injector and HEDS section.

Our primary measurement section is in the initial part of the HEDS injector, utilizing quadrupole magnets and wire scanners (Fig. 2.). A beam dump is positioned between the IPM3 and IPM4 wire scanners to minimize beam loss during measurements, with the first three profile monitors in use during machine physics experiments. Quadrupoles QF1, QF2, QD3, and QF4 (highlighted in green) operated at currents of 2.1, 6.25, 112.5, and 6.35 Amperes, respectively. Wire scanners 1, 3, and 4 were used for the three-screen method, while wire scanner 3 (IPM3) was employed for quadrupole scans and tomographic phase space reconstruction. The parameters for the beamline and its configuration are provided in Table 1.

RESULTS

The ISIS injector was modelled using Parmila and Trace-3D beam dynamics codes, with simulation results shown in Fig. 3 and Fig. 4. Horizontal and vertical beam profiles, measured with the IPM3 wire scanner under various quadrupole settings and rotation angles, are presented in Fig. 5. Applying maximum entropy techniques, commonly used in image processing, the transverse phase space distributions at the injector linac's output were calculated and shown in Fig. 6. We used three screen monitors and quadrupole scan procedures to benchmark these calculations against topographically reconstructed phase spaces. Beam phase space ellipse

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calculated from three screen monitoring procedure are shown in Fig. 7. Also, the curve extracted from fitting to quadrupole scan beam sizes at IPM3 are represented in Fig. 8. Transverse Twiss parameters and unnormalized emittances, simulated and modelled by three methods, are summarized in Table 2, with average unnormalized RMS emittance values of 0.98 and 1.31 π·mm·mrad for the horizontal and vertical directions, respectively. The strong alignment between simulations, measurements, and different methods provides a solid basis for further accelerator physics studies and future machine learning applications.

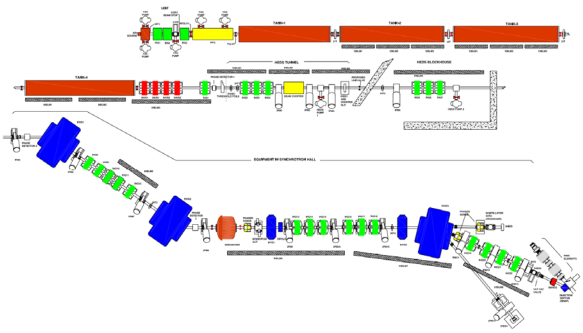

Figure 1: ISIS injector and HEDS setup.

Table 1: Beamline Parameters at the Measurement Location

Element	Length (meters)	Strength /Current
D1	1.804	
QF1	0.292	$0.91m^{-2}$/2.1A
D2	1.3452	
QF2	0.292	2.698 m^{-2}/6.25A
D3	0.229	
QD3	0.311	-5.062 m^{-2}/112.5A
D4	0.229	
QF4	0.292	2.741 m^{-2}/6.35A
D5	0.2	
D6	6.32	
D7	6.32	

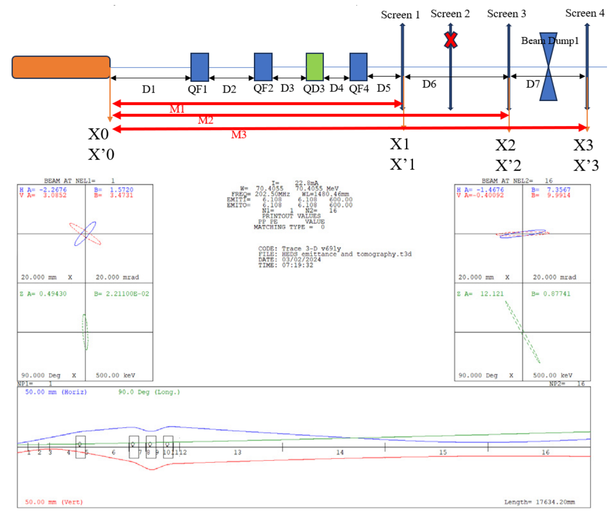

Figure 2: Layout of measurement setup in HEDS.

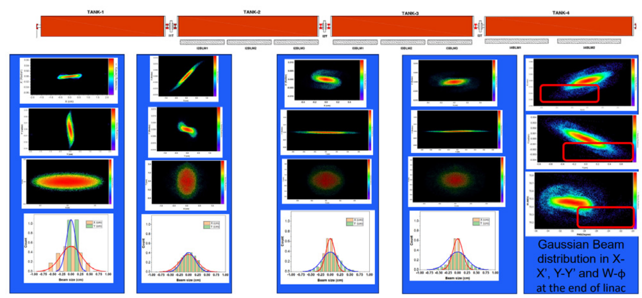

Figure 3: Simulation of the ISIS injector DTL using Parmila.

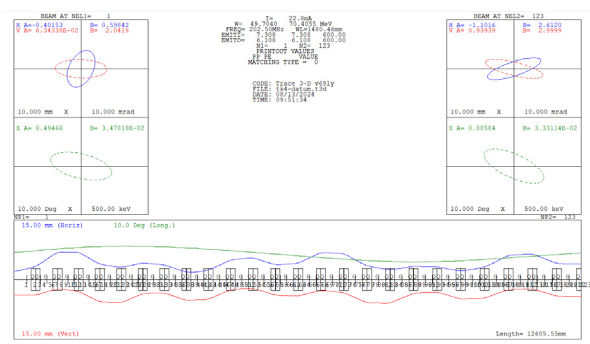

Figure 4: Simulation results of ISIS beam dynamics from Tank-4 input to output.

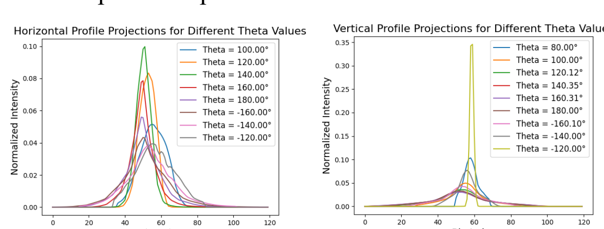

Figure 5: Beam profiles measured in IPM3 for each rotation angle: Horizontal (Left) and Vertical (Right).

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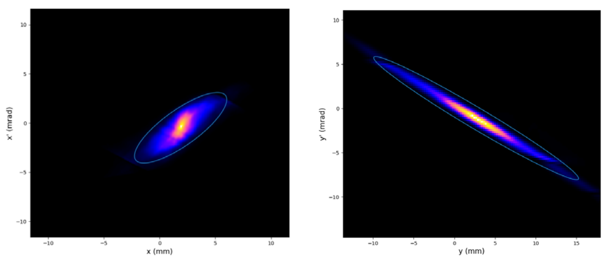
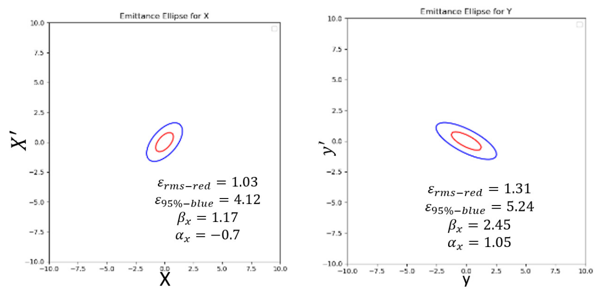


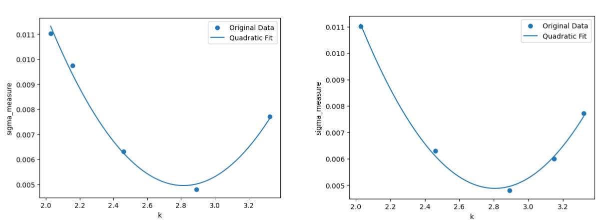
(a) (b)

Figure 6: Tomographically reconstructed phase space: (a) Horizontal, (b) Vertical.



(a) (b)

Figure 7: Beam phase space ellipse calculated from three-screen monitoring setup: (a) Horizontal, (b) Vertical.



(a) (b)

Figure 8: Quadratic fit to the quadrupole scan data.

Table 2: Twiss Parameters and RMS Emittance Calculated From Simulations and Measurements

	Trace	**Parmila**	**Three screen monitors**	**Quad Scan**	**Tomographic reconstruction**
αx	-1.1	-1.22	-0.7	-1.5	-0.83
βx	2.61	1.97	1.17	4	1.18
αy	0.93	1.19	1.05	1.5	4.5
βy	2.61	2.8	2.45	4	8
ε_{rms-x} mm.mrad	1.22	0.85	1.03	1.15	0.8
ε_{rms-y} mm.mrad	1.22	0.92	1.31	1.15	1.79

CONCLUSION

Emittance at the injector's output was measured using three different methods, which agreed well with simulations and can aid in automating the tuning of the HEDS section of the ISIS accelerator. Tomographic reconstruction based on maximum entropy is valuable for analysing beam phase space nonlinearities critical for upgrading the current machine and designing ISIS-II. Beam profiles in the x and y directions were measured at 70.5 MeV in the HEDS section, providing a solid foundation for future machine physics studies and upgrades.

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