THE ISIS TRANSVERSE EMITTANCE SCANNERS AND SOFTWARE

S. R. Lawrie, D. C. Faircloth, A. P. Letchford, C. Gabor

ISIS, Rutherford Appleton Laboratory, STFC. Chilton, Oxfordshire, OX11 0QX, United Kindgom.

S. Jolly, J. Pozimski, P. Savage

Department of Physics, Imperial College, London, SW7 2AZ, United Kingdom.

Abstract

An overview of the hardware and software used to study the transverse emittance on the ISIS Pulsed Spallation Neutron Source at RAL is given. Vertical and horizontal slit-slit emittance scanners are used for high resolution measurements. Data acquisition and analysis is performed using in-house written C# code. Alternatively, a pepperpot head can be used to record both the emittance and beam profile simultaneously, with data analysed using Matlab code.

INTRODUCTION

The transverse emittance of the H⁺ ion beam at ISIS is measured part-way through the threesolenoid Low Energy Beam Transport (LEBT) using horizontal and vertical slit-slit scanners. An identical pair of scanners is used on the Ion Source Development Rig (ISDR) [1], which is the test bed for ion source modifications at ISIS. It allows a comprehensive study of how the beam characteristics change when using experimental ion source components, without having to disrupt the user schedule of the operational source. There is additional diagnostic equipment on the ISDR than on the ISIS injector; however the ion source and emittance measurement routine is essentially identical, so this paper will mostly focus on the ISDR, with the slit-slit measurements equally applicable to ISIS. The Front End Test Stand [2] currently being constructed at RAL will also use these emittance measurement techniques to study the beam at low energy.

Figure 1 shows the arrangement of the equipment on the ISDR. A Penning-type surface plasma ion source creates a 55 mA H⁺ beam with energy of 35 keV. Immediately after the ground plane of the system is a diagnostics vacuum vessel. Horizontal and vertical slit-slit emittance scanners are mounted transverse to the beam axis. An extra device which is not included on the ISIS injector is a scintillation detector which can travel along the axis of the beam to measure its downstream profile. An optional pepperpot emittance measurement device can be mounted in place of the profile detector. To avoid collisions, the slit-slit scanning arms must be safely parked away from the beam when operating the pepperpot head and vice versa. Additional instruments used on the ISDR to study the beam include an energy analyser, beam current transformer and a space-charge compensating buffer gas delivery system; however this paper will focus solely on the emittance measurement apparatus.

SLIT-SLIT EMITTANCE SCANNERS

Hardware

The slit-slit scanner hardware [3], shown in Figure 2, consists of two slit arms positioned one after the other along the beamline which can each move a total of 64 mm across the beam. These arms are then mounted on a main arm, capable of moving up to 180 mm to bring the slit arms in line with the beam. The front slit arm holds a 0.25 mm wide slit to sample positions in the beam. The rear slit arm holds a 0.08 mm slit followed by a Faraday cup to measure the current of the position-sampled beamlet as a function of angle. These two slits hence allow a high-resolution measurement of the transverse phase space of the $H^-$ beam. The slits are separated by 20 mm, so the angular resolution is 4.0 mRad. The three arms are driven by McLennan stepper motors which move to an accuracy of 1.25 $\mu$m per step, so the angle range may be oversampled if necessary. A 500V suppression electrode at the Faraday cup removes secondary electrons. Commands are sent to the stepper motors using the Windows Serial Communication Library for C++ (WSC4C) and data signals are read from the Faraday cup using a Data Acquisition Processor (DAP) from Microstar Laboratories.

![FIGURE 2(a). A slit-slit emittance scanner.](image)

![FIGURE 2(b). Horizontal and vertical scanners mounted on the ISDR diagnostics vessel.](image)

Software

The scanning software is written in C# using the Microsoft Developer Studio .NET. C# uses the same coding style and memory management control as C and C++, but enables much simpler implementation of powerful Windows-based GUIs. A typical view of the software is given in Figure 3. The software performs four functions: Calculate the necessary positions of the slits and send signals to the WSC4C in order to perform a complete scan; Allow manual control of each arm should the need arise; Perform data analysis and emittance calculations on measured data, and save and load several datasets for comparison. These functions are described in detail below.

Multiple Document Interface

The slit-slit scanner software is an entirely self contained, Windows-based system. This being the case, the overall main (parent) screen contains all the standard menus such as File, Edit and Window, as well as a set of custom toolbar buttons. Inside the parent screen are smaller (child) windows, in which the data is displayed, stored and analysed. The child windows are independent of each other so the user can, for example, be taking a new set of data from the slit-slit arms in one window whilst analysing data from several other previous scans, each in their own window. One can also set the axis scaling in the parent window such that all the open data sets are shown on the same scale for easy comparison. Windows are automatically arranged for tidy viewing.
Multi-threading

Some of the features in the program require intense and sustained computer processing time; for example when a scan is being taken. In most programs one comes across, processes are completed in a single, linear chain. Any attempt to interrupt a process that takes a very long time to complete generally leads to a system crash. However, the emittance scanners must be reliably interruptible in case the user wants to abort a scan for some reason.

Additionally, the display must be continually updated to show newly acquired data and hence indicate the progress of the scan. Moreover, if the user wishes to analyse previously saved data whilst a new scan is in progress, the system must be able to complete both tasks concurrently. For these reasons, the emittance scanner software is multi-threaded throughout, enabling multiple processes to be completed simultaneously and the user to have full control at all times.

Data Display

The dominant feature of each child window is a histogram plot of the 2D phase space data at a certain time interval in the beam pulse. The histogram’s colour map can be changed to a variety of styles (for example ‘Hot’ or ‘Jet’) to allow comparison with Matlab analyses. The time in the beam pulse is easily changed via a slider. The 2D histogram can be replaced by a 1D integrated profile of the beam to give a feel for the beam’s real-space shape. There is the facility to enhance the contrast of low intensity portions of the beam so that, for example, otherwise unnoticed faint wings stand out much more from background noise.

1D slices through the phase space data giving intensity as a function of angle and position are shown to the left and bottom of the histogram plot, respectively. Slider bars on the x and x’ axes of the 2D plot allow the user to take these intensity slices at any position or angle.

High resolution, pre-cropped images of each of the plot panels can be captured for direct insertion into publications.
Scanner command input and real-time information

A region of the screen is devoted to displaying real-time commands sent and received to/from the stepper motors. This allows the user to see exactly what the motors are “thinking” at all times; often preventing confusion as to why the motors have momentarily paused during the scanning routine. Additionally, a mock-up of Windows Hyperterminal is implemented to allow the user to send manual commands to the motors, should the need arise.

Config Files

No data referring to the set-up of the emittance scanner arms are hard-coded into the software. Instead, data such as the maximum travel distance of the slit and main arms are imported from a config file associated with each emittance scanner apparatus. This ensures that the scanning routine is equally accurate on both the ISDR and ISIS slit-slit scanners – despite them having slightly different apparatus set-ups – without having to modify the code.

Data Analysis

There are numerous tools to correct errors, analyse data and assist in the calculation of emittance in the software. For example, the user can:

- Integrate the intensity data and plot as a function of time to use the program as a crude beam current monitor to compare the beam pulse shape with that measured on an oscilloscope.
- Add a bias to the data in case the background noise is not centred on zero.
- Cut out data points below a certain percentage of the maximum intensity so only those data above a certain threshold value are included in emittance calculations.
- Perform a Lagrange polynomial interpolation fit to the background to remove any drift which may have been added due to secondary electron currents at the Faraday cup or capacitive discharge in the current amplifier.
- Remove individual data pixels which have abnormally large or small intensities far from the beam core and hence would drastically affect emittance calculations.
- Repair a column of data (representing one position sample) which may have become shifted due to a high voltage breakdown prematurely activating the data acquisition trigger. As this repair is performed by interpolating across existing data points either side of the affected column, this does not detract from the accuracy of emittance calculations.

Emittance Calculations

The emittance of the beam can be calculated in the same software used to acquire the data, removing the need to transfer data between various software packages. As well as saving time and computer memory, this approach ensures consistent, comparable results. The emittance is calculated using either a threshold cut or using the Self Consistent Un-Biased Elliptical Exclusion (SCUBEEx) method [4]. For rigorous emittance calculations, SCUBEEx is more useful as it is both unaffected by background bias and has a straightforward and self consistent error calculation built in. Nevertheless, taking threshold cuts give reasonably accurate values of emittance much quicker, so this is still a useful tool.

Since the beam is sampled at small time intervals (typically 10 µs) within each pulse, it is possible to monitor how the emittance varies as a function of time. This is useful in case a significant part of the pulse has an emittance which does not fit in the acceptance of the accelerator. Again, the SCUBEEx method gives error bars to this plot. Overall, the emittance of the ISIS beam is very well understood using the slit-slit scanners and data analysis software.
PEPPERPOT EMITTANCE MONITOR

An additional technique to measure the beam emittance, which is currently only used on the ISDR, is a pepperpot head; shown in Figure 4. Intercepting the beam with a tungsten mask drilled with holes, both the vertical and horizontal emittances can be measured simultaneously. In addition, the real-space profile of the beam can be seen using the raw data, making the pepperpot head a versatile tool to characterise the beam [5].

![FIGURE 4(a) The copper plate and tungsten mask of the pepperpot head.](image)

![FIGURE 4(b) The movable stage on which it is held. This is seen attached to the diagnostics vessel in Fig. 2b.](image)

**Hardware**

The pepperpot head is mounted on an arm capable of travelling longitudinally along the beam path by a total of 700 mm, driven by a high-torque motor accurate to 10 μm. This allows one to monitor how the profile and emittance of the beam grow under the influence of space charge in the drift space following the ion source. Longitudinal motion is also useful in order to benchmark the pepperpot emittance calculations with the slit-slit results by positioning the pepperpot head in the same plane as the slit-slit scanners.

The H beam is position sampled by intercepting it with a 41 x 41 grid of 50 μm holes separated by 3 mm in a tungsten mask. The resulting beamlets then travel a distance of 10 mm to a quartz scintillator. To prevent beamlets crossing each other, they pass through 2 mm diameter holes in a copper plate. Vertical and horizontal angular divergence of the beamlets is then determined by measuring the position shift of the scintillation spots relative to the sampling holes they originated from. This method hence measures the four-dimensional phase space in one device.

To measure the divergence angle of the beamlets, the positions of all 1681 sampling holes must be precisely known to the accuracy of one pixel. During operation, the pepperpot head and CCD camera may move or become skewed relative to one another, so calibration lines are etched into the copper mount which ensure the absolute positions of the holes is known. A calibration image is taken for every beam scintillation image to ensure reliable results. Example images taken with the pepperpot are given in Figure 5.

![FIGURE 5(a) Calibration image.](image)

![FIGURE 5(b) Scintillation spot image.](image)

![FIGURE 5(c) Reconstructed beam profile.](image)
Software

The data gathered from the pepperpot is a lot more difficult to analyse than from the slit-slit scanners. A comprehensive Matlab program is used for this task, as shown in Figure 6. The software first of all calculates the exact positions of each sampling hole using the calibration lines. It must then pick out each scintillation spot and determine its centre. This is sometimes difficult due to the light contrast levels or asymmetric spot shapes. The skew of the image is then corrected for before the horizontal and vertical angular divergence is calculated.

![FIGURE 6. The graphical user interface of the pepperpot emittance analysis software.](image)

The emittance is calculated in two methods. As a first estimate, the emittance using just the centres of each scintillation spot is used. This method artificially reduces the emittance due to the lack of data points and hence current. The more accurate but time consuming method is to smooth data between the spots and use the intensity of each pixel in the image to generate the phase space plot and calculate the emittance. Although the errors in the calculated emittance are increased due to the smoothing process between the spots, the per-pixel resolution within each spot is very fine at 70 µm. Overall, calculated emittance values match favourably with those from the slit-slit scanners, as shown in Figures 7 and 8. The ability to cover the 4D phase space in one device, as well as being able to generate particle distributions for use in tracking codes, makes the pepperpot an extremely useful tool.

![FIGURE 7(a) Horizontal slit-slit scanner data of a typical beam](image)  ![FIGURE 7(b) Pepperpot emittance plot of the same beam](image)
Figure 8. Comparison of the horizontal and vertical emittances calculated using the slit-slit and pepperpot scanners when varying the H\textsuperscript{-} beam extraction voltage.

CONCLUSION

Highly versatile and complementary emittance measurement systems are used on the injector and the Ion Source Development Rig at ISIS. The slit-slit scanners provide highly accurate phase-space plots, but are limited in speed and scanning range. The pepperpot covers a wider area of the beam, can travel longitudinally along the beam path and captures the full four dimensional phase space in one shot, but gives data which is more difficult to analyse. Together, these two systems work extremely well to fully characterise the emittance of the H\textsuperscript{-} beam from the ISIS Penning ion source.

REFERENCES