**Baseline D-Pace Emittance Scanner Licensed from TRIUMF rev 1.doc**

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| Agreement: | License Agreement between TRIUMF & D-Pace |
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| Rev 1 Edits: | Added "Chinese Journal of" to 1st reference in section 3 per M. Stockli email 28/03/2008 |

## (1) Introduction:

D-Pace, Inc. has licensed an Allison type emittance/phase space scanner technology from TRIUMF. D-Pace is in the process of commercializing this technology. This means that D-Pace is at present undertaking the transfer of the technology documentation from TRIUMF (drawings, design notes, reports, papers, know-how etc..), and undertaking development to transform a laboratory device to a turn-key commercial device.

D-Pace has also begun to commercially market the baseline emittance/phase space scanner, and should initial sales be forthcoming the first commercial emittance scanner device would be manufactured at TRIUMF with the assistance of D-Pace staff. This is an important part of the technology transfer, and it also enables commercial sales to be undertaken with minimum risk to the customer, since TRIUMF will be engaged to make the first commercial unit. Subsequent units would be manufactured by D-Pace. It is anticipated that if an order is placed for multiple units, substantial per/unit cost savings can be obtained by the customer.

## (2) Why Have an Emittance/Phase Space Scanner?:

An emittance/phase space scanner provides more information than simply the magnitude of the emittance in either the xx' or yy' phase planes as a function of a percentage of the beam contained within the ellipse corresponding to the emittance.

The TRIUMF Allison-type scanner technology licensed by D-Pace, Inc. provides the beam intensity distribution in the xx' phase plane, or by rotating the device by 90 degrees (or by utilizing a second scanner) one can measure the beam intensity distribution in the yy' phase plane. In other words, this is a 3D representation which can be visualized with a 3D plot, or a contour plot. Of course, beam intensity as a function of either x or x' (or y or y') can also be displayed as a 2D plot. The software associated with the scanner can also determine phase space ellipses representing the ion beam in either the xx' or yy' phase plane that contain any percentage of the total beam intensity desired. Or a 4rms emittance can be computed. The corresponding beam sigma matrix co-ordinates can be computed for any ellipse.

This information is very important. To accurately model what will happen when a charged particle beam is transported through an ion-optical system (beam transport system), it is essential to know the beam's phase space representation at the input to the system. The beam representation must be known as either a phase ellipse with an associated emittance for a specified percentage of the beam contained within the ellipse (which has been computed based on the measured beam characteristics), or as the actual distribution itself.

The TRIUMF licensed emittance/phase space scanner technology can measure, compute, and display these important low energy ion beam characteristics. To optimize low energy ion-optics design, beam transport, and beam matching it cannot be over-emphasized how important it is to have an accurate measurement of the beam intensity distribution in xx' and/or yy', and the corresponding computation of emittance and xx' and/or yy' phase ellipse characteristics for charge particle optics modeling purposes.

## (3) Background Information about Allison Type Scanners:

This section refers heavily to descriptions and a figure obtained from the following paper:

> Stockli M.P., Chinese Journal of High Energy Physics & Nuclear Physics, Vol. 31, Supp. I, 2007, 182-186.

The original publication for this type of scanner is:

> Allison P.W., Sherman J.D., Holtkamp D.B., IEEE Trans. Nucl. Sci., 1983, NS-30: 2204-2206.

The largest trajectory angle to be measured was first published in:

> Stockli M.P. et al, AIP CP749, Melville, NY, 2005, 108-111.

Allison and collaborators combined an electric trajectory sweep technique with a mechanical beam position sweep. This is a good compromise in terms of the various techniques that can be utilized to measure the beam intensity distribution in xx' or yy' phase planes. All that is required is a slit followed by a single electric deflector followed by a second slit and finally a single Faraday cup all mounted within a solid "scanner head" as illustrated in Figure 1. A solid scanner head ensures accurate alignment of the two slits which is important for low divergence beams.

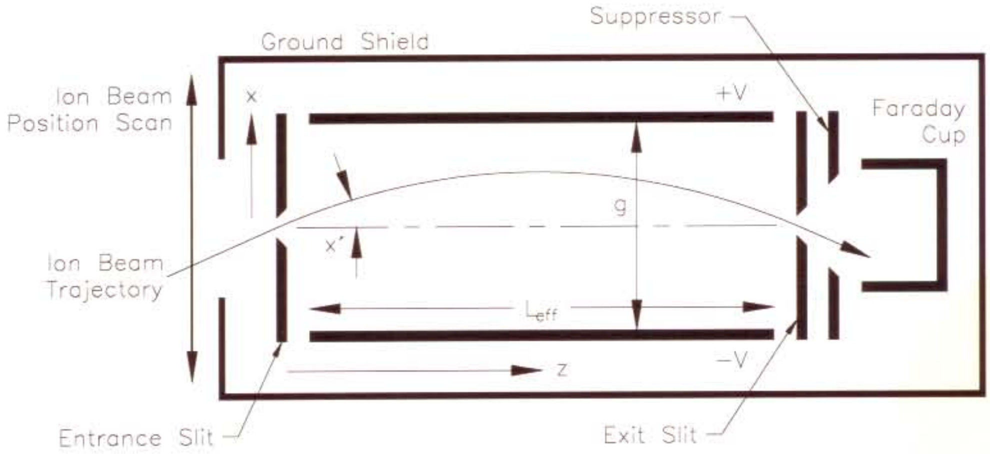


**Figure 1:** Illustration of an Allison Type Emittance/Phase Space Scanner Head.

The electric deflector plate shown in Figure 1 has an effective length " $L_{eff}$ " and gap " g ". Ions with energy per unit charge of " U " and an angle " x' " require deflection voltages " ±V" of:

$V = 2 \cdot U \cdot x' \cdot (g/L_{eff})$ or $x' = V \cdot L_{eff}/(2 \cdot g \cdot U)$
The gap limits the angular acceptance to:

$x'_{max} = 2 \cdot g/L_{eff}$

This leads to the design equation for the limit of the voltage supplies to " $V_{max}$ ", where:

$V_{max} \approx (x'_{max})^2 \cdot U_0$

Where " $U_0$ " is the highest ion energy per charge that can be accommodated and " $x'_{max}$ " is the largest trajectory angle to be measured.

## (4) The Baseline TRIUMF Allison-type Scanner Specifications Licensed by D-Pace:

D-Pace has licensed the TRIUMF emittance/phase space scanner shown in Figures 2 & 3. Figure 2 illustrates that the scanner is positioned through a linear actuator, stepper motor, and accurate screw jack system. The scanner always re-positions itself against start blocks prior to a scan to ensure repeatable measurements. The scanner head is water-cooled, and also utilizes limit switches so that the stepper motor does not drive the scanner head beyond prescribed limits. D-Pace can provide the scanner mounted in a custom vacuum box with o-ring or metal seals as desired by the customer.

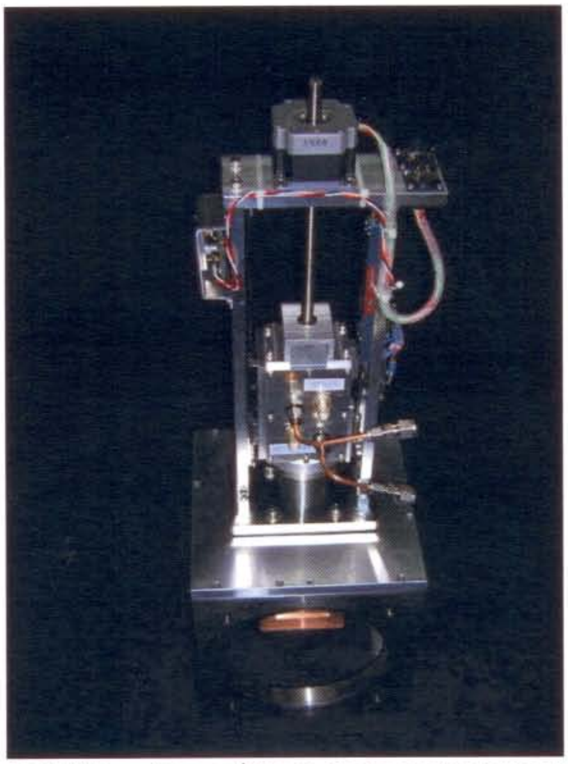

**Figure 2:** A view showing the TRIUMF emittance/phase space scanner mounted in a vacuum box.

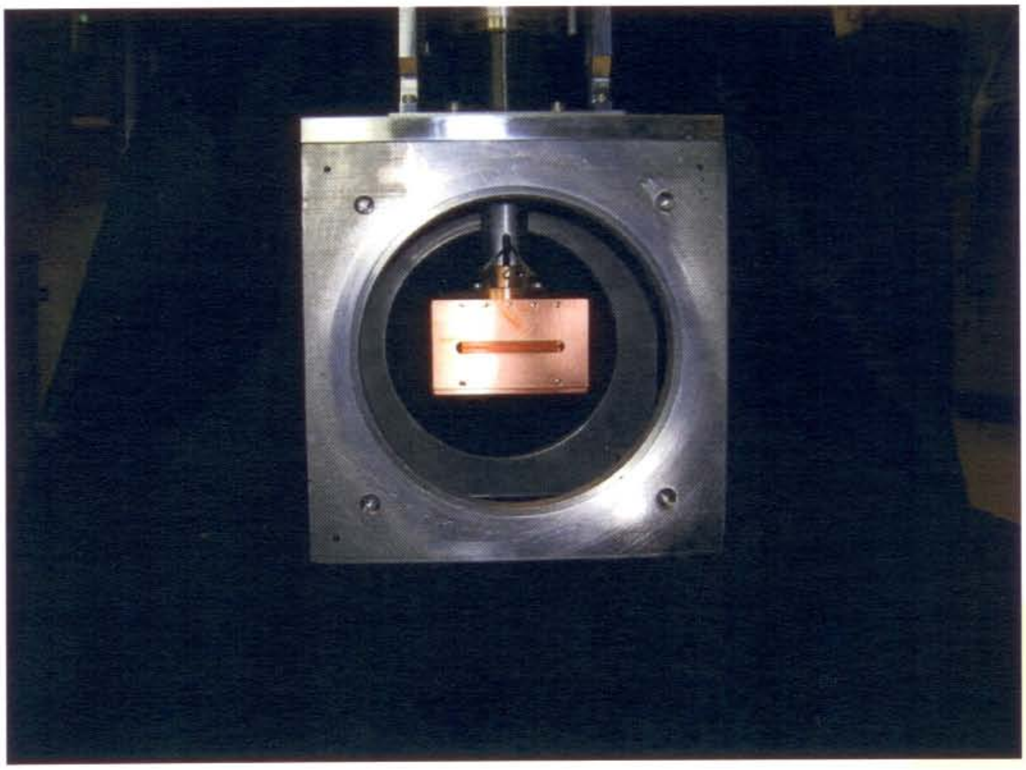

**Figure 3:** A picture showing the entrance slit in the "scanner head". In this orientation, the scanner head is swept vertically in position, and the electric beam trajectory sweep is in the vertical direction also. Therefore, the beam intensity distribution in the (y, y′) phase plane is measured in this case.

BASELINE TRIUMF EMITTANCE/PHASE SPACE SCANNER SPECIFICATIONS:

1) U = 300,000 Volts (i.e. 300 keV, $H^-$ which corresponds to 300,000 eV per unit charge)
2) $x'_{max}$ = ±0.035 Radians = ±35 milli-Radians*
3) $V_{max}$ = 500 Volts
4) Slit Length = 50 mm
5) Slit Separation = 0.025 mm
6) Scanner Head Stroke = 100 mm
7) Typical Position Scan = 50 Mechanical Steps
8) Typical Trajectory Scan = 100 Voltage Steps
9) Typical Scan Time = 2 Minutes
10) Maximum Beam Power = 300 Watts
11) Position from Mounting Flange to Beam Centre = Adjustable
12) Vacuum Box = Optional – can be custom designed for length/width/height & flanges
13) Beam intensity distribution in only one phase plane is measured by the scanner i.e. (current, x, x′), or if scanner position rotated by 90 degrees in the vacuum box then one can also measure the phase plane (current, y, y′). Or two scanners can be purchased to obtain beam intensity distributions (current, x, x′) and (current, y, y′).
14) Scanner comes complete with: Electronics half-rack with controllers, power supplies, I/O, and computer. Necessary cables and connectors. Terminal, Key Board, Mouse. Software for operating the scanner, performing calculations, and displaying the data.

*If the customer is measuring ion beams with a higher energy per unit charge ratio than U = 300,000 Volts then a smaller $x'_{max}$ will be available. Conversely, if ion beams with a lower energy per unit charge ratio than U = 300,000 Volts are being measured then a larger $x'_{max}$ will be available.

RESOLUTION: Usually a quick preliminary scan is done to determine the region of interest for the beam. In the case of a typical 300 keV $H^-$ beam at TRIUMF, for example, the beam may be found to be roughly 12 mm by 30 milli-Radian in extent. The scanner software permits the user to define a region of interest that just encloses the beam in phase space. For example, for a centred beam the scan limits could be set for a scan from –6 mm to 6 mm, and from –15 milli-Radians to 15 milli-Radian, and 50 mechanical steps are chosen for the positional beam sweep and 100 voltage steps are chosen for the trajectory angle sweep then this results in a resolution of:

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| Positional Resolution: | 12 mm/50 = | 0.24 mm |
| Angular Resolution: | 30 milli-Radians/100 = | 0.30 milli-Radian |

The baseline specifications for the TRIUMF scanner are provided above, and the customer may utilize the equations of section 3 to establish the validity of the TRIUMF device for their own application (i.e. each customer will typically be interested in ion beams of different energy to charge ratio " U ", different size in millimeters, and different divergence angles in milli-Radians). Or, the customer specifications can be provided and the applicability of the TRIUMF device can be determined by D-Pace staff. Some aspects of the baseline design can be easily customized if necessary. For example, maximum voltages up to 1000 Volts could be accommodated, stroke length and slit length could be adjusted fairly easily. Other changes could be accommodated, but would require significantly more up front re-design work.

## (5) The Graphical User Interface and Software:

A typical display of the data is shown in Figure 4. The TRIUMF software performs the following:

1) Operation of the scanner head:
    a. Park Scanner Head against reference blocks.
    b. User may specify scanning start position and end position in position.
    c. User may specify number of mechanical steps to be taken through positional range.
    d. User may specify scanning start position and end position in angle.
    e. User may specify number of voltage steps to be taken through angular range.
2) Data Analysis and presentation:
    a. The angular and positional centering of the beam can be determined.
    b. The beam intensity distribution as a function of position can be plotted (2D).
    c. The beam intensity distribution as a function of angle can be plotted (2D).
    d. The beam intensity distribution as a function of position and angle can be plotted as either a 3D plot or a contour plot.
    e. Emittances and Ellipse parameters can be computed corresponding to a user specified percentage of the beam intensity enclosed.
    f. Emittance as a function of beam fraction can be plotted (2D)
3) Interface:
    a. MATLAB script to allow user interaction with the phase space plot.
    b. Multiple plot windows.
    c. 3D rotatable plots.
    d. Pick data files from an interactive file chooser.
    e. Output plots in a multitude of formats for easy publication.
4) Other Software Features:
    a. Background can be estimated and subtracted.
    b. The region where the primary beam signal is can be specified by the User, so that this region can be excluded from the background estimation.
    c. The user can identify ripple (a common spurious signal) and have it fitted, and subtracted.
    d. Parts of phase space containing spurious peaks, or peaks that belong to undesired ion species can be selected by the user and erased.

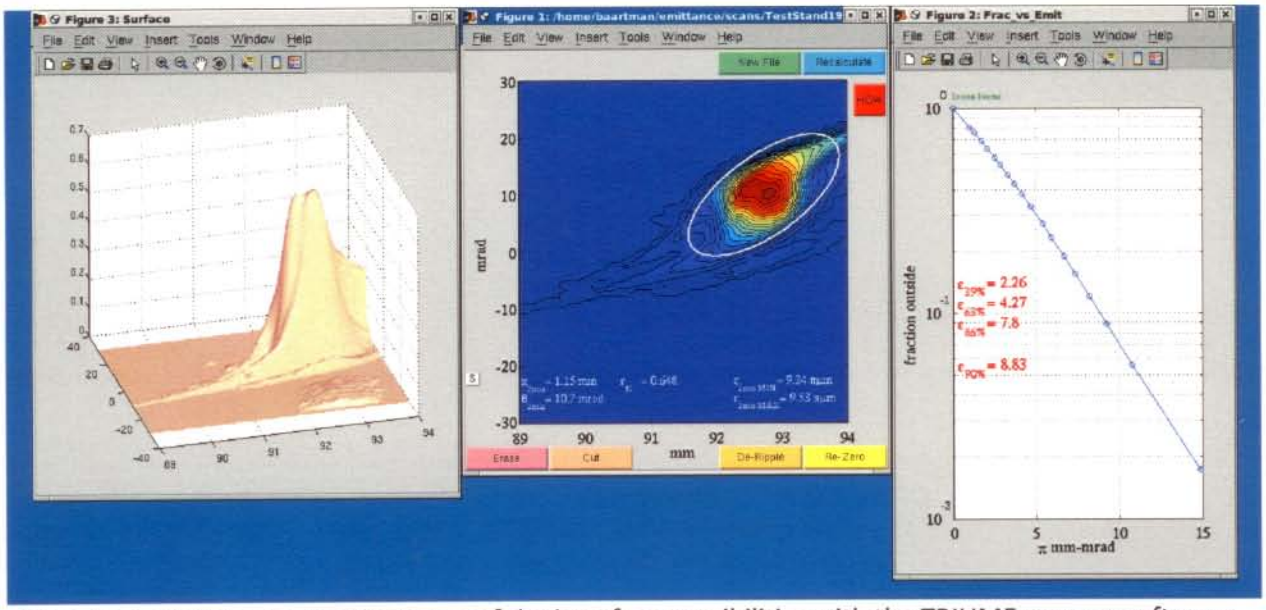

Figure 4: A graphic representing some of the interface possibilities with the TRIUMF scanner software.

## (6) Conclusion:

This document presents the baseline (i.e. nominal) information for a TRIUMF Aliison-type Emittance/Phase Space Scanner licensed by D-Pace, Inc. The purpose of the document is to advise potential customers of the basic specifications, so the applicability of the device to the customer's requirements can be ascertained. D-Pace also wishes to receive the specific details, constraints, and specifications for each customer's application, this will permit D-Pace to ascertain whether the baseline design is appropriate, or whether the scanner design must be customized or developed further in some fashion. D-Pace is also interested to receive brief descriptions of existing scanner technologies that some potential customers may already be using in their laboratory, institute or company. Such information related to different technologies currently in use for emittance measurement would also be helpful in providing a possible direction for future research and development.