# ALLISON SCANNER EMITTANCE DIAGNOSTIC DEVELOPMENT AT TRIUMF

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*Abstract*

TRIUMF has developed Allison scanners to measure the transverse emittance of both low intensity hadron beams at $10^4$ pps (1.6 fA) and high intensity electron beams at 10 mA for a dynamic range of $10^{13}$ in intensity. The devices give high-resolution transverse emittance information in a compact package that fits in a single diagnostic box. This paper discusses the design and performance of the operating devices, and the technologies introduced. For clarity it is divided in two main parts: the first part deals with the low intensity emittance scanner and the second part with the high intensity emittance scanner.

## ALLISON SCANNER - CONCEPTUAL DESIGN

The Allison type emittance scanners [1] are high-resolution scanners, which consist of a front slit, deflecting plates, a rear slit, and a Faraday cup in a single unit that is stepped across the beam with a stepper motor. At each stepper position, the beamlet selected by the front slit is swept across the rear slit with the deflecting plates and the transmitted current measured as a function of deflecting plate voltage by the Faraday cup: see Figure 1.

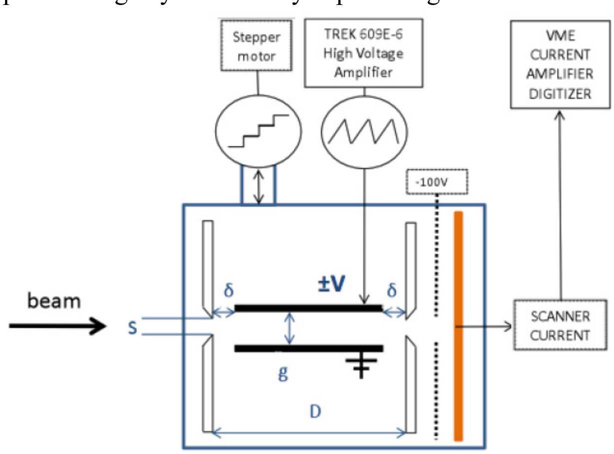


Figure 1: Emittance scanner schematic

The maximum analyzable angle, limited by particles striking the plates is given by the geometry:

$$x_m' = \pm 2g/(D + 2\delta)$$

For non-relativistic particles, the voltage across the plates was derived by Allison et al [1]. The phase-space area resolution is given by $s^2/D$.

## PART I – LOW INTENSITY EMITTANCE

### *Introduction*

A low intensity emittance scanner was needed for the radioactive ion beams in the ISAC facility at TRIUMF. The initial ISAC (Isotope Separator Accelerator) emittance scanner was an Allison type emittance scanner [1], which was installed in the LEBT section after the mass separator in 1998, when the beamline was built. This emittance scanner contains a Faraday cup that can measure below 1 pA. However, since the typical beam's phase space area of 30 mm-mrad is a thousand times larger than the scanner resolution of $s^2/D$=0.03 mm-mrad, it is not practical to analyze beams of less than 1nA. Since most of the beams delivered to the ISAC experiments are much below 1nA, a device capable of measuring emittances for low intensity radioactive beams and help characterize the ion beam created is necessary. An upgraded scanner was designed, installed and tested in 2013.

### *Design*

In the new design the Faraday cup at the end of the emittance scanner is tilted and a channeltron (Channel Electron Multiplier) is incorporated: see Figure 2.

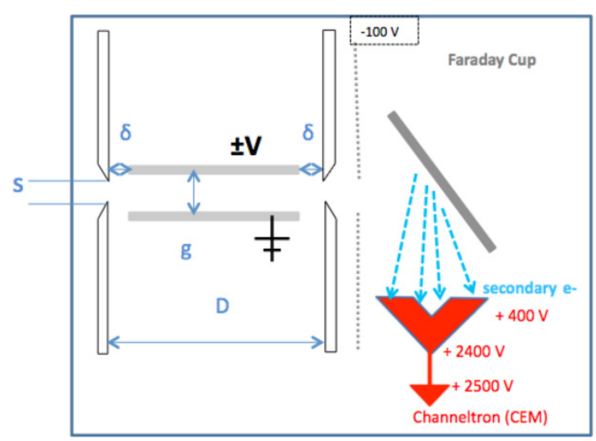


Figure 2: Emittance scanner with CEM schematic

Dimensions g, D, δ, s are given in Table 1. The power supply of the electrostatic plates is a KEPCO power supply with a maximum voltage of ±1,000 V.

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In this case the ion beam passing through both slits, strikes the Faraday cup, creating secondary electrons. When a potential is applied between the input and the output end of the CEM (see Figure 2) the secondary electrons are captured, multiplied and an electron pulse for every incident ion is counted at the anode. In this mode of operation the beam emittance is plotted indirectly from the secondary electrons. This mode is used for very low intensity ion beams, mainly for radioactive ion beams of 100 pA to $10^4$ pps (1.6 fA). For beam intensities above 1 nA this model can also perform a “traditional” scan: reading and plotting directly the ion beam current intercepted by the Faraday cup.

Table 1: Design Parameters

| | |
|---|---|
| E [keV] | 60 |
| L [mm] | 50 |
| D [mm] | 53 |
| δ [mm] | 1.5 |
| g [mm] | 2 |
| s [mm] | 0.038 |
| $x_m$’ [mrad] | ±75.5 |
| $V_m$[V] | ±770.75 |
| El_F $_m$[V/mm] | ±385.39 |

Design parameters for the emittance scanner are given in Table 1. To achieve high phase-space area resolution of 0.03 µm, the slit gap for both entrance and exit slits is chosen as 0.038 mm. A model of the mechanical assembly is shown in Figure 3.

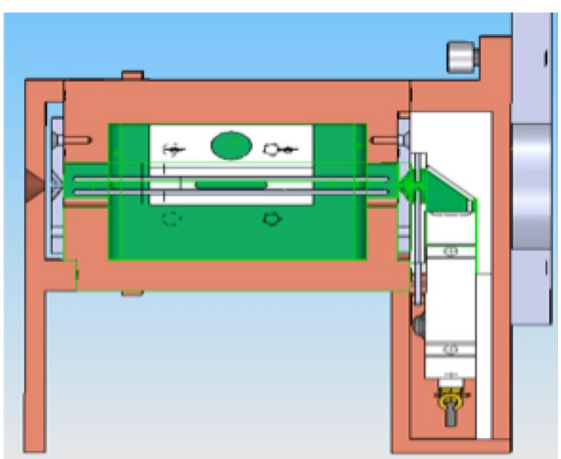

Figure 3: Assembly model of the Emittance scanner with CEM.

Electrostatic simulations using COMSOL Multiphysics were done to determine the width of the channeltron and its location. Electrons are launched from the surface of the Faraday cup at 10 eV kinetic energy, at different angles: between 90 deg and 135 deg, from different positions: +/- 40 mrad from the beam axis, with +400 V applied on the channeltron surface and -100 V on the bias ring.

The channeltron captures all electrons launched under the above conditions, when:

- the Faraday cup plate is tilted at 45 deg
- the on-axis distance between the exit of the second slit and the Faraday cup plate is 10.5 mm
- the distance between the center beam axis and the channeltron is 4 mm
- the channeltron is 7 mm wide and 21 mm long

### *Engineering and Materials*

The selected channeltron is a CEM-KLB2107 model from Dr. Sjuts Optotechnik GmbH [2]. It has an extended dynamic range, with a resistance of 70 MOhm. Its gain is given in Figure 4.

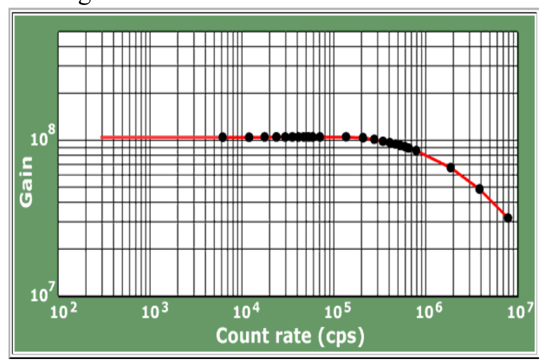


Figure 4: CEM Gain as a function of count rate [2].

The High Voltage bias is applied to the channeltron via a voltage divider (see Figure 5) such that its entrance is kept under +400 V. The voltage applied across the device is varied in the range 2000-3000V depending on the required gain. The signal from the anode through a decoupling capacitor is fed to a HFAC-26 preamplifier (Becker-Hickl) and to a discriminator. If the average current from the channeltron exceeds 1uA the preamplifier drives high the overload output, which shuts off the High Voltage power supply. This measure protects the device from an occasional exposure to excessive beam currents. Logical signals from the discriminator are passed to a counter. The measured count rate represents the secondary electron intensity and is therefore proportional to the ion beam intensity. The system is capable of processing secondary electron intensities from tens to about $10^6$ particles per second.

The emittance scanner’s function is to diagnose the radioactive ion beam and the mass separator setup. It is installed in a diagnostic box, on a moving platform. When a scan is initiated, the platform serves to move the scanner in place of the mass selection slit. It then either steps through the beam with a chosen step size to measure the horizontal emittance figure, or another motor rotates it 90 degrees and then steps vertically to measure the vertical emittance figure.

Mechanically the scanner is designed such that the channeltron can be replaced without impacting the alignment. The end part of the scanner, housing the bias ring, the Faraday cup and the channeltron, can slide and be replaced in situ. The slits and the electrostatic plates are not affected by the replacement of the channeltron: see Figure 3. The channeltron has a limited lifetime around $5 \times 10^{12}$ accumulated counts. To allow replacement of the

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channeltron and Faraday cup in situ, LEMO connectors were mounted on a plate fixed to the emittance scanner body.

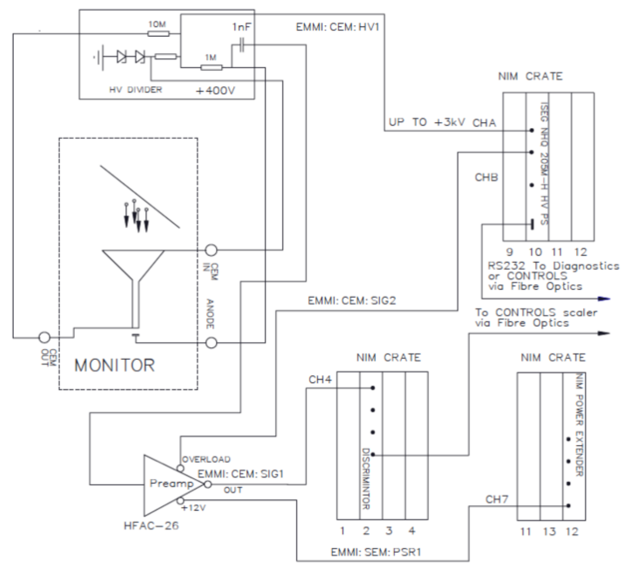


Figure 5: Emittance Meter with CEM Electronics Schematic.

Coaxial and triaxial (with the two outer shields grounded together) Kapton insulated cables type 28 AWG, 50 ohm were selected to assure a good shielding of the signals.

Innovative Tool & Die Inc. in Canada manufactured and aligned the tantalum slits. The rest of the machining and the assembly were performed at TRIUMF.

## *Installations and Controls*

The emittance scanner software is a subroutine running under the control of EPICS [3].

There are two sources of scan data selected from the emittance scan user interface:

- Faraday cup using a VME current amplifier
- channeltron using a VME scalar

The default configuration for the scalar is to present a count rate of counts/second. This may be modified to match the requirements of the emittance scan. At each scan position a delay is introduced to allow for voltage sweep settling time before reading the Faraday cup or the channeltron. In the case of the channeltron it is important that the sampling rate of the scalar is twice this time to prevent aliasing. Thus for a delay of 0.5 seconds the scalar sampling rate must be set to 0.25 seconds. In the present implementation the scalar sampling rate must be set manually; this can be error prone. We plan to automate this so that any user adjustment of the emittance scan delay will automatically set the scalar to the correct sampling rate and also normalize the data to counts/second.

The selected scalar model is Joerger VSC16 [4] with the following specifications: 16 channel, 32 bit, 40 Mhz VME up/down, pre-settable scalar.

## *Performance and Results*

As an example, Figure 6 shows a comparison of Faraday cup emittance meter scan and CEM emittance meter scan. The top scan shows the emittance scan for a $^{7}$Li ion beam at 22.5 keV, using the normal current-based measurement. The total current was about 10 nA.

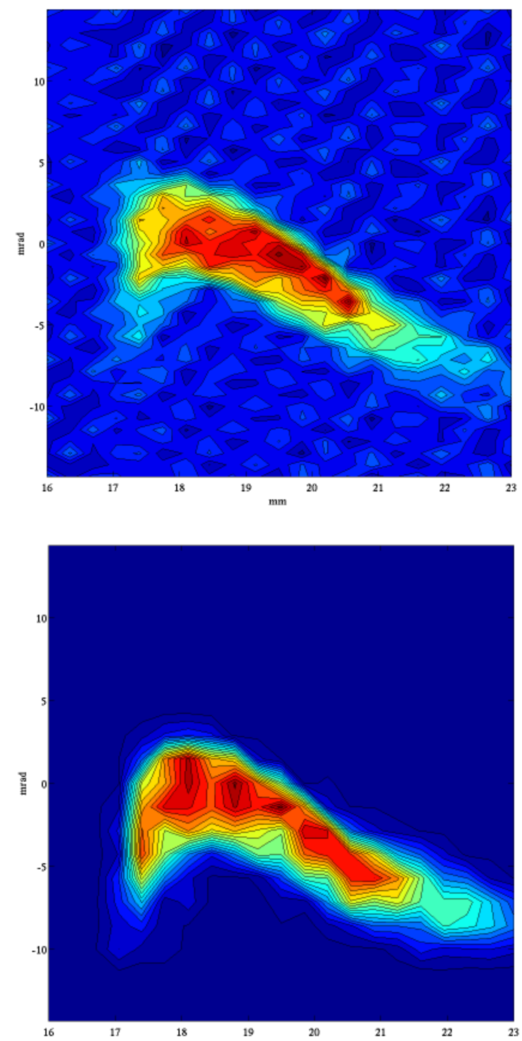


Figure 6: Comparison of Faraday cup emittance meter scan (top) vs. CEM emittance meter scan (bottom).

These are vertical emittance scans, ions coming from Niobium Oxide target FEBIAD ion source taking 14 µA of proton beam. Notice the level of background noise. This noise is about ±1 pA in one pixel.

The bottom scan is using the new CEM-based current measurement. This is for a $^{27}$Al ion beam at 22.5 keV, and the total current is only 1 pA. This is 10,000 times less current and yet the noise is far less. Gain in sensitivity is roughly a factor of 1 million.

During commissioning some noise was detected even when no-beam scans were taken. This noise was traced to the stepper motors. To cure it, ferrite boxes were mounted in series with the drivers of the stepper motors.


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### *Conclusions*

We have successfully demonstrated ability to measure detailed emittance figures for beams of intensity down to 2 fA: a factor $10^6$ sensitivity improvement compared with the conventional technique. This has allowed diagnosis of radioactive beams directly, instead of relying on analogue stable beams. For example, we have often conjectured a significant difference between the laser-ionized radioactive beam and the surface-ionized stable beam. It is now possible to make such investigations.

## PART II – HIGH INTENSITY EMITTANCE SCANNER FOR ELECTRONS

### *Introduction*

An electron linac (e-linac) is being installed at TRIUMF as part of the ARIEL project to produce rare isotope beams via photo-fission. The final specified energy and current are 50 MeV and 10 mA. The source for the e-linac is a gridded thermionic electron gun (e-gun) that will operate at 300 kV. An electron gun test stand operating at 300 kV was installed for initial beam tests. The source is modulated at a frequency of 650 MHz, and can be operated with a macro pulse structure to allow duty factors from 0.1 % up to c.w. operation.

A variety of beam diagnostics has been installed in the test stand to characterize the electron beam. A high intensity emittance scanner, installed downstream of the e-gun, was proposed for testing and optimizing the source parameters, at low and high duty factors, at different RF conduction angles and solenoid settings. TRIUMF's previous experience with Allison type scanners [1] are for characterizing pulsed $H^-$ beams at 12 to 300 keV and 100 µA (30 W maximum), and for c.w. heavy ion beams at 60 keV and a few nA as related in the previous section. For the electron beam it was decided to re-engineer the scanner for higher beam intensity and power density [5]. As the original specification of the electron source was for 100 keV beam the design requirements were: 10 mA c.w. beam at 100 keV, for a beam diameter of 10 mm full width. Also, since the e-gun operates at $10^{-9}$ Torr, the technology and materials used for the scanner are required to meet UHV standards. Thus the scanner assembly is installed on a 6 inch conflat flange.

### *Conceptual Design*

The conceptual design and scanner functionally were described in the first part of this paper. For relativistic particles, the voltage $V_m$ is smaller by a relativistic factor $k$:

$$V_{m-rel} = V_m / k$$

and

$$k = 2/(1 + 1/\gamma)$$

### *Design*

See Table 2 for a summary of the chosen design parameters.

Table 2: Design Parameters

| Beam Energy | 60 keV | 100 keV | 300 keV |
|---|---|---|---|
| D (mm) | 49 | 49 | 49 |
| δ (mm) | 2 | 2 | 2 |
| g (mm) | 3.5 | 3.5 | 3.5 |
| s (mm) | 0.038 | 0.038 | 0.038 |
| k | 1.06 | 1.09 | 1.23 |
| $V_{m\text{-}rel}$ (V) | ±2,337 | ±3,773 | ±10,046 |
| $x'_m$ (mrad) | ±132 | ±132 | ±132 |
| Electric field (V/mm) | 668 | 1,078 | 2,870 |

### *Engineering and Materials*

See Figure 7 for an overview of the emittance scanner head and assembly.

A detailed description of the device can be seen in an earlier paper: see reference [5]

### *Installation and Controls*

Prior to installation in the beam line the emittance scanner was cleaned to UHV standards by degreasing in an ultrasound bath. Material testing was done in a dedicated UHV test chamber. Baking was done directly *in situ* flowing hot air at 200 deg C through the cooling lines. However, this method affected the alignment of the scanner and will not be consider in the future.

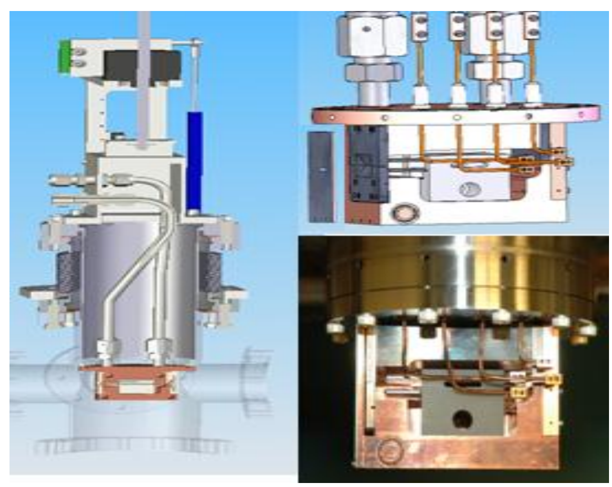

Figure 7: Emittance scanner head and assembly.

Also, more information regarding the Controls implementation can be found in an earlier paper: see reference [5].

### *Performance and Results*

Scans were taken at 60 keV and 300 keV for different peak beam intensities, from 3 mA to 11 mA, and duty cycles ranging over 0.1% to 99%. The scan shown in Figure 8 is for a beam *rms* size of 2.69 mm at 11 mA, 660 W or 30 W/mm$^2$. In a 0.03 µm pixel of phase space, this is 4 µA at the peak of the emittance figure. The noise is around 1 nA on this gain range. This allows detail down to the 98% contour.

The data file, consisting of 6561 current readings, 81 positions and 81 voltages or angles in this particular case, is processed and contour-plotted using a MATLAB script.

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At high beam power levels, the processing includes background subtraction: the current in the pixels along the lower edge of the emittance plot, where the beam is entering the first slit but deflected too far to make it through the second slit, is used to characterize this background. It measures a few nA and arises from the electrons liberating positive ions by striking the deflection plates. A solenoid is used to adjust the beam size and power density. It is found that the entry slit closes from thermal expansion above ~115 W/mm$^2$ in agreement with earlier estimates. These scans are characterized by an anomalous dip in the centre of the emittance figure that disappears at lower duty factors. The *rms* emittance for the data of Fig. 3 is found to be 10.1 µm, while the 39% emittance is 7.1 µm. For a perfectly Gaussian beam, the *rms* emittance and the 39% emittance are equal. The enlarged *rms* emittance is due to the "bowtie"-shaped distortion evident in the figure. The origin of this kind of distortion is thought to be space charge combined with a non-optimal Pierce geometry of the electron gun; it is under investigation. Scans were taken at a number of different duty cycles for the same gun setting (same RF amplitude, cathode bias and solenoid current) confirming that the emittance was unchanged. After the first set of measurements the scanner was inspected on the bench. Signs of copper vaporization from the back of the protective plate (made of tungsten explosively bonded to copper) onto the tungsten slits were seen. For future designs of the front protective plate the copper part on the back of the plate will be removed near the edges of the collimation gap, instead of pure tungsten an alloy would be used for easy machining and since pure tungsten becomes brittle through thermal cycling; so the protective plate would consist of a thicker layer of tungsten alloy explosively bonded to a thicker copper layer. The tungsten slits were checked under the microscope and found to be undamaged. No other components were damaged due to the direct impact of the high power beam.

### *Conclusions*

The new Allison scanner, with a phase space area resolution of 0.03 µm, has measured beam emittances up to 725 W of electron beam power, in a high vacuum environment. Beam investigations using the scanner are on-going and the device is proving essential for optimizing the electron gun. For fixed source parameters the beam phase space is unchanged while varying from 10% to 99% duty cycle at 11 mA peak current. Also, the emittance measurements are consistent with independent measurements using a scintillator-type profile monitor, and a simple analytic model for a thermionic gun.

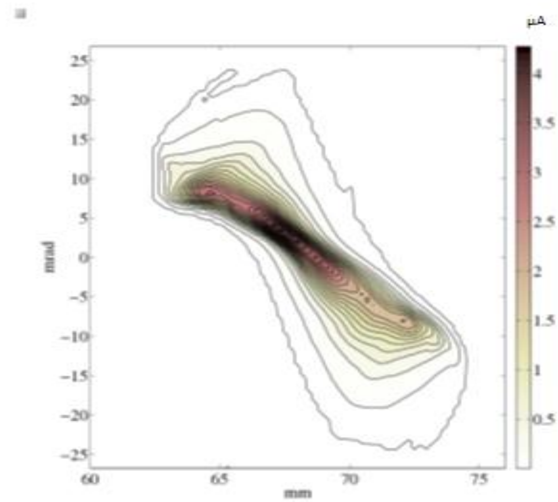


Figure 8: Emittance scan at 60 keV and 11 mA (660W).

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