HIGH POWER ALLISON SCANNER FOR ELECTRONS

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Abstract

TRIUMF has designed, built and commissioned an "Allison" emittance scanner for electrons up to 300 keV in energy and average power up to 1 kW. Transverse phase space as large as 1600 π um can be measured with a resolution of 0.03 μ m, in a high vacuum environment 10⁻⁹ Torr. This paper discusses the engineering challenges of designing an Allison scanner for a high intensity electron beam, the components and materials used, as well as the technologies introduced. Also included are experimental results of first tests at 60 keV with a thermionic electron gun, up to 660 W at 99% duty factor. Emittance contours were measured at high resolution for a variety of focusing conditions and intensities.

INTRODUCTION

An electron linac (e-linac) is being designed and 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 100 kV is 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, and Pierce electrode angles. TRIUMF has previous experience with Allison type scanners[1] although the applications are for characterizing beams of lower power i.e. for 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. For the electron beam it was decided to re-engineer the scanner for higher beam intensity and power density. The design requirements are: 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" CF flange.

CONCEPTUAL DESIGN

An Allison scanner consists 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 Fig. 1.



Figure 1: Emittance scanner schematics.

Dimensions g, D, δ , s are given in Fig.1. The maximum analyzable angle is given by the geometry:

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

For non-relativistic particles, the voltage across the plates was derived by Allison et al[1]. But, 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

The phase-space area resolution is given by: s^2/D .

Table 1: 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	
$V_{m-rel}(V)$	±2,337	±3,773	±10,046	
$x'_{m}(mrad)$	±132	±132	±132	
Electric field (V/mm)	668	1,078	2,870	

In order to satisfy the design requirements without jeopardizing the quality of the scans, the length of the deflecting plates is chosen to be as long as possible within the boundary of a flange of 88.9 mm diameter. This defines electrostatic plate lengths of 45 mm, for a total

^{*} TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada. ARIEL & e-linac construction are funded by BCKDF and CFI

scanner length of 60 mm. The top plate is biased at high voltage and the distance δ between the electrostatic plates and the pair of slits upstream/downstream of them is fixed at 2 mm. The electrostatic plate gap g is 3.5 mm to allow a sufficient maximum analyzing angle. 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. See Table 1 for a summary of the chosen design parameters.

ENGINEERING & MATERIALS

See Fig. 2 for an overview of the emittance scanner head and assembly. The emittance scanner body (l x w x h = 60 mm x 44 mm x 45mm) is made of OFHC Copper (oxygen free high conductivity copper), selected for its high thermal conductivity and for machining purposes. The copper is explosively bonded to stainless steel (SS), with the SS forming a vacuum flange of 88.9 mm diameter and 6.35 mm thickness. The flange seal is a very light ESI spring energized C-Ring made of silver plated Inconel. Less than 5,000 pounds clamping force is required to compress the seal, so very light non-magnetic SS hardware is used. Tests indicate that the leak rate of this sealing configuration is in the range of 10^{-11} at-cc/sec.

The water-cooling system has an offset configuration, integrated into the emittance head, which introduces an overall asymmetry to the scanner design and opens it on one side, allowing for better vacuum pumping conditions. The cooling is achieved through two parallel water lines of 0.25 inch diameter directly machined in the OFHC copper and sealed by electron beam (EB) welding. The water enters and leaves the head from its top (vacuum flange) part, through two VCR fittings TIG-welded directly on the emittance head body. To preserve the UHV, the main supply and return cooling lines are placed inside an inner tube at atmospheric pressure. Here the assembly is arranged in the form of an atmospherevacuum-atmosphere sandwich.

Upper and lower jaws of the front slit and the top back jaw are made of tungsten, chosen for its high melting point, low thermal expansion coefficient and low vapour pressure. The bottom back jaw is part of the emittance head body, made of OFHC copper. It was CNC machined then aligned and wired EDM (electron discharge machine) together with the bottom-front tungsten jaw, which was dowel pinned after the alignment. The bottom jaws are parallel and coplanar with respect to each other to 2.5µm. The top jaws are removable and have a step to assure the slit gap. Measurements of the front and back slit widths were taken under the microscope prior to the installation in the beam line. The front slit is protected by a removable collimator plate with 1.25 mm aperture, made of tungsten explosively bonded to copper (3 mm total thickness), which stops most of the high power beam and efficiently removes the heat through thermal conduction.

ANSYS steady state thermal simulations were conducted for simplified 3D models and different homogenous beam intensities and sizes. See Table 2 for some relevant figures. In summary, the present limiting

factor is the power density on the front slit; densities in excess of $\sim 115 \text{ W/mm}^2$ will close the slit through thermal expansion.

The electrostatic plates, made of SS, are held in place by aluminium nitride insulators (AlN), selected for their UHV performances, such as low porosity and low outgassing at very high temperature. Four feedthroughs are EB welded directly in the emittance head SS flange: two for the electrostatic plates and two for the Faraday cup integrated into the emittance scanner. The bottom electrostatic plate can be either grounded or biased, to eliminate the asymmetric fringe field and to reduce the scanning voltage. The Faraday cup has a secondary electron suppressing ring. The four wires for signal and voltage are Kapton insulated, with the exception of the Faraday cup signal, which is shielded (coaxial cable). All wires are placed in the inner tube at atmospheric pressure and they can withstand high temperature and X-ray radiation.

Table 2: ANSYS Thermal Simulations Analysis

Beam Energy [keV]	60	100
Beam diameter [mm]	2	10
Beam intensity [mA]	6	10
Power density [W/mm ²]	115	10
Slit Temp [deg C]	1,650	300
Front plate Temp [deg C]	445	560
Thermal expansion [µm]	33	<<10

The explosive bonded materials are made by High Energy Metals, Inc. in USA. The AlN insulators are manufactured by Omley Industries, Inc. in USA. The EDM and wire EDM of the tungsten material is done by Innovative Tool & Die Inc. in Canada. The rest of the machining (EB welding, CNC machining) and the assembly were performed at TRIUMF. The special ESI vacuum seal is manufactured by Parker Hannifin Corporation in USA.



Figure 2: Emittance scanner head and assembly.

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.

Emittance scans are initiated from an EPICS GUI which communicates with a VME EPICS IOC running under Linux. The following types of VME modules[2] are employed: stepping motor controller for positioning the slit; DAC for controlling the voltage ramp; and variable gain current amplifier/digitizer for the current measurement. The number and size of mechanical steps and the range and size of the voltage ramp are selected via the GUI interface. The scan parameters: position, voltage and current data are written to a file and made available to emittance analysis software.

The present readback device has a 10 Hz update rate so the emittance scanner has a variable delay with a minimum value of 100 ms, so a coarse emittance scan of 21 positions by 21 angles takes 58 seconds and a more detailed scan of 81 positions by 81 angles takes 700 seconds.

PERFORMANCE AND RESULTS

Scans were taken at 60 keV for different peak beam intensities, from 3 mA to 11 mA, and duty cycles ranging over 0.1% to 99%. The scan taken at the highest beam power is for a beam *rms* size of 2.69 mm at 11 mA, 660 W or 30 W/mm² and is shown in Fig. 3. In a 0.03 μ m pixel of phase space, this is 4 μ A 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. In principle, more orders of magnitude sensitivity are available: a similar scanner installed in our radioactive beam facility can measure currents to the pA level.

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. 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/mm² 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 μ m, 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 the copper part on the back of the plate will be removed near the edges of the collimation gap. The tungsten slits were checked under the microscope and found to be undamaged. No other components were damaged.

CONCLUSION

The new Allison scanner, with a phase space area resolution of $0.03 \mu m$, has measured beam emittances up to 660 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 3: Emittance scan at 60 keV and 11mA (660W).

REFERENCES

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