# Emittance Measurement Techniques Used in the 1 MeV RFQ for the PET Isotope Linac at Fermilab

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***Abstract***: Beam emittance measurements have been performed on the $^{3}$He$^{+}$ beam at the PET-isotope production accelerator, being commissioned at Fermilab for the Biomedical Research Foundation in Shreveport, Louisiana, USA. Emittances have been measured at injection to and extraction from the first RFQ, at 20 keV and 1 MeV, respectively. A single slit followed by a 48-electrode collector is used in the standard way to measure the divergence of the $^{3}$He$^{+}$ beam as a function of position. Noise reduction operations have been developed, both in hardware and software. These techniques and the emittance measurement results are presented.

## 1. INTRODUCTION

Fermilab, in collaboration with Scientific Applications International Corporation (SAIC), the University of Washington and the Biomedical Research Foundation (BRF), is commissioning a linac to produce an average 200 particle µA of $^{3}$He$^{++}$ at 10.5 MeV for the production of the radioisotopes needed for PET, positron emission tomography [1]. Since isotopes with half-lives on the order of minutes are desired, a small accelerator which can exist in a hospital environment is being constructed. $^{3}$He is interesting because it may reduce neutron radiation and the shielding requirements, thereby reducing the cost, the complexity and the weight of the accelerator. The purpose of this effort is to explore the overall practicality of this approach.

| | Component | Energy | Description | Len |
|---|---|---|---|---|
| 1 | Ion Source | 20 keV | Duoplasmatron | 0 m |
| 2 | Transfer Line | 20 | Solenoid | 0.7 |
| 3 | 212 MHz RFQ | 1.0 MeV | | 1.024 |
| 4 | Transfer Line | 1.0 | 540° bend | |
| 5 | 425 MHz RFQ A | 5.047 | Tightly coupled | 1.371 |
| 6 | 425 MHz RFQ B | 8.025 | | 1.461 |
| 7 | 425 MHz RFQ C | 10.539 | | 1.485 |
| 8 | Target Area | 10.539 | Solid or Liquid | |

Table 1, Components of BRF PET Linac.

The components in this accelerator are summarized in Table 1 and shown schematically in Figure 1. The basic layout of this accelerator is as follows: 25 mA of singly-charged $^{3}$He is extracted from a duoplasmatron source at 20 keV into a 0.7 m transfer line and injected into a 212 MHz RFQ. This RFQ accelerates the beam to 1.0 MeV at which energy the $^{3}$He$^{+}$ is stripped by a gas jet to doubly-charged $^{3}$He. Following the stripper, a 540° isochronous bend rebunches and injects the beam into the beginning of three tightly-coupled 425 MHz RFQs. The bend has the added benefit of folding the accelerator back onto itself, reducing the length of the accelerator. The beam is accelerated to 10.5 MeV and terminated at the target area where the isotopes are created. The repetition rate of this accelerator is ≤360 Hz, for a maximum duty factor of 2%.

Extensive test of the first RFQ, including tests of the gas stripper, have been conducted. The remaining parts of the accelerator will be commissioned in the Fall of 1996. Delivery to BRF in Louisiana, USA, is scheduled for early 1997.

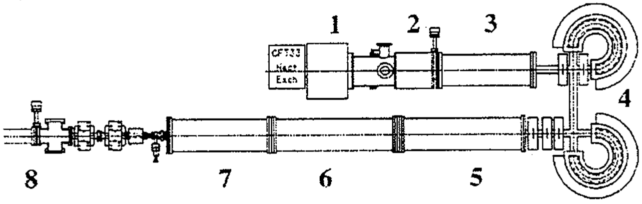

*Figure 1, The BRF PET Linac*

Further information on this project is available from our web site: `http://www-linac.fnal.gov/pet`, and in Reference [1], in this conference.

This paper is organized as follows. The hardware and software components used in this measurement are presented. Then the unique features of this measurement are described, in particular, the way in which noise is eliminated from the data, both programmatically and manually. Finally, specific results are presented.

## 2. SETUP

### 2.1. *Hardware.*

The emittance probe which has been used at Fermilab for a number of years is used here [2, 3]. The probe consists of a 0.075 mm slit in a thin tungsten plate, followed at a distance of 55 or 98 mm by a bank of 48 copper strips, separated by mylar insulators. The probe is adjustable in length for beams of differing divergence. Each strip subtends 3.34 mrad or 1.87 mrad respectively with respect to the slit. A stepping motor on a precision drive moves the probe through the beam. The resolution of the stepping motor and drive is 0.05 mm. Only one probe is available, so the opposite plane is measured by removing and rotating the probe assembly by 90-degrees. The wire signals are sampled synchronous to the beam at 10 Hz.

To minimize RF and ground noise, the collector strips are fully shielded by the emittance probe assembly, the cables are shielded, and the cables pass through high-µ metal tape cores outside the vacuum chamber. Each of the 48 signal cables is terminated in 50Ω at a bank of low noise amplifiers. These amplifiers have a gain of 200 with common mode noise reduction. The amplified signal is sampled, held and digitized by the local controls computer. The digitization resolution is 14 bits or 1 mV for signals of -10 to +10 V. Typical peak signals are a few volts. Noise levels and off-

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sets are less than a few tens of mV, which causes some problems, see below.

### 2.2. *Software.*

There are five software components used in the emittance measurement. All except the first are run on a host console, an 85 MHz Sun SPARCstation 5 running the Solaris 2.4 operating system.

1. A local control algorithm is run in the local controls computer, the IRM (Internet Rack Monitor) [4], to manage the movement of the emittance probe through the beam. Parameters to this local application (LA) include: the start and stop positions, the step size and the minimum acceptable beam current. The LA provides binary status on data validity, i.e., when the probe has completed a step AND the beam current is adequate.
2. The data acquisition program is responsible for setting the parameters for the LA according to the desires of the experimenter, and for collecting the valid emittance data. This program writes the raw emittance data to a disk file on the host console when the measurement is complete.
3. An analysis program reads the file generated by program 2 and converts the raw data into analyzed emittance data and writes a fixed-format data file suitable for display. It also prints the emittance of the beam in several ways: the RMS emittance and the geometric emittance for 60%, 90% and 95% of the beam. (All emittance levels are contained in the program; only these are presented.) These percentage emittances are calculated by appropriately adding up the pixels of beam in *x/x'* phase space. Cuts on the data and noise reduction, described below, are carried out here. Note that the raw data file is unaffected.
4. Several options for the display of the data are possible. The one used here is LabVIEW [5].
5. Utilities for viewing or manipulating the raw data are available.

In addition to these fundamental programs, simple launch programs have been created using TCL/TK and LabVIEW to orchestrate the running of these programs. The LA is written in the C programming language; the programs in 2, 3 and 5 are written in C++, and the display program is written in LabVIEW.

## 3. MEASUREMENTS

Measurements have been made at two energies for the $^{3}\mathrm{He}^{+}$ beam: at injection to the RFQ at 20 keV and at extraction from the RFQ at 1.0 MeV. The low-energy measurements are made by replacing the RFQ with the emittance hardware at the entrance to the RFQ.

### 3.1. *Data Reduction*

An uncut measurement is shown in Figure 2a. With noise and offset levels amounting to a few percent of the peak signal, it is clear that noise reduction is needed. Noise elimination has been performed by algorithm and by hand.

Algorithmic noise reduction consists of first removing obvious offset levels for each wire. Then all values less than a user set "NoiseValue", typically tens of mV, are set to zero. If the noise is not adequately eliminated, specific noisy wires may be removed from the calculation.

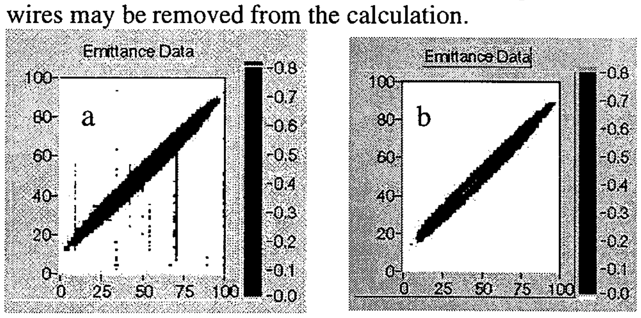


Figure 2, Before (left) and after application of noise cuts.

Small, non-zero readings on the edge of the distribution, where there is clearly no beam, unrealistically enlarge the calculated RMS emittance. (These extraneous signals also increase the 100% emittance, but this is of less concern.) To eliminate this effect, a further cut may be applied to the data. The RMS emittance is calculated from the noisy data, after passing through the background subtraction described in the previous paragraph. All data outside of an $X\sigma$ ellipse (where $X$ is a value supplied by the experimenter, usually about 8.0) of the same aspect ratio and tilt as the calculated emittance are removed, and a new RMS emittance is obtained. This cut may be repeated with the new RMS emittance, but it is found that only the first iteration is necessary. For highly elongated or distorted ellipses this cut may actually chop off real beam at the ends of the distribution. The effect of these operations is shown in Fig 2b.

The beam in these measurements does not fill a regular phase-space ellipse, so the cut described above does not eliminate noise uniformly. So, manual reduction has been done on a few measurements. A procedure has been developed where the raw data are exported into a spreadsheet program. First, the data are corrected and zeroed as in the computer algorithm method. Next, the edges of the beam are identified visually within the spreadsheet, and all data outside of this edge are manually zeroed. Then the RMS emittance is computed by hand or the raw data are written back into a (new) data file, and analyzed programmatically with no further cuts. After some practice, the raw data can be manipulated in this manner in about two hours.

Manual reduction of the data gives significant insight into the sensitivity of various noise components. Small noise points near the real emittance distribution are of little or no significance to the RMS emittance calculation. However, a single noise point some distance from the real distribution has a strong effect on increasing the calculated RMS emittance. RMS emittance and twiss values obtained by hand from the raw data gave good (better that 10%) agreement with the computer reduced data.

### 3.2. *20 keV Emittance*

Properties of the transport line and the effect of the solenoid magnet on the beam parameters at injection to the first RFQ have been measured. Beam parameters are measured at approximately the entrance point of the RFQ for magnet currents from zero to 300 A. Figure 3 shows the *x/x'* phase space plot for the beam near a waist at the emittance probe (225 A in the solenoid, 3181 Gauss). The simulation program TRACE-2D is then used to match parameters to the expected beam conditions from the ion source and these data. To obtain a match, full neutralization of the $^3He^+$ beam is assumed. The ion source emittance is taken to be 160 to 200 mm mr. The beam at the emittance probe is 400 mm mr with an 80% core of 200 mm mr. Using twiss parameters from this analysis allows a calculated match to the RFQ for the core of the beam. The normalized RMS emittance near the 20 keV entrance of the RFQ is 0.6 mm mr.

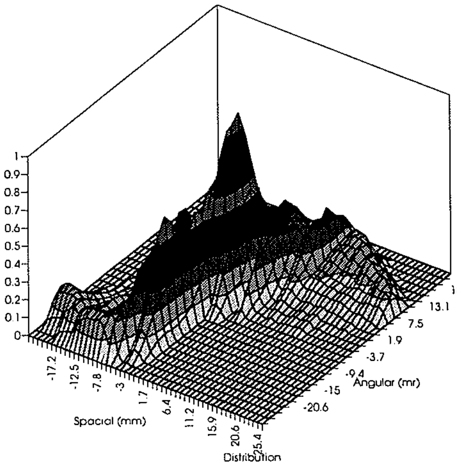


Figure 3, 20 keV Emittance contour plot.

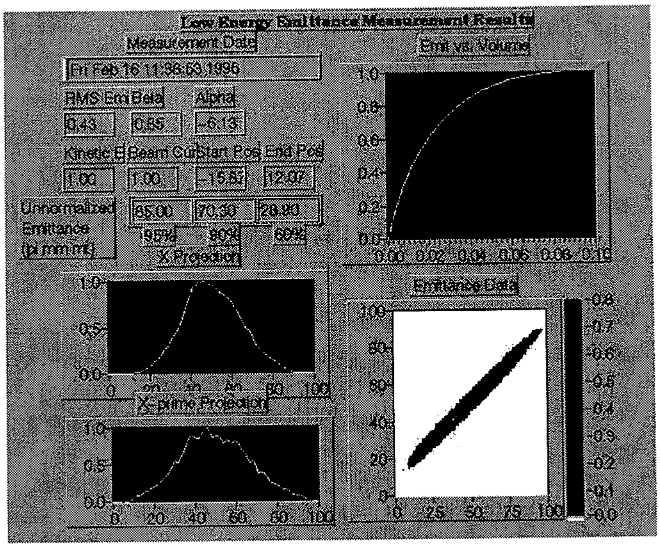
It would be useful to measure the emittance immediately at the exit of the ion source with the present equipment as information of the ion source beam is based on much earlier and lower current studies and on EGUN calculations.

### 3.3. *1.0 MeV Emittance*

The emittance of the 1 MeV $^3He^+$ beam has been measured as a function of the orientation and sample time within the 70 μsec beam pulse. For these measurements the beam current at 20 keV is similar to above, but the injection line is configured differently and with a weaker solenoid so only 5.5 mA is seen at the exit of the RFQ. For different orientations and sample times through the macropulse, there is essentially no change in the emittance or the twiss parameters of the beam: the beam at 1 MeV appears symmetrical and uniform in time. Thus the emittance for a 5.5 mA 1 MeV $^3He^+$ beam is measured to be:

| | |
|---|---|
| Normalized-RMS Emittance | 0.20 mm mr |
| beta | 1.7 m/r |
| alpha | -6.9 |
| 95% emittance | 43 mm mr |
| 90% emittance | 34 mm mr |
| 60% emittance | 13 mm mr |

A typical run as seen through the LabVIEW interface is presented in Fig. 4.


Low Energy Emittance Measurement Results

Measurement Date: Fri Feb 16 11:36:53 1996

RMS Emi: 0.43 Beta: 0.65 Alpha: -6.13

Kinetic E: 1.00 Beam Cur: 1.00 Start Pos: -15.87 End Pos: 12.07

Unnormalized Emittance (pi mm mr): 95%: 85.00 90%: 70.30 60%: 28.90

Figure 4, Emittance of 1 MeV beam, as seen through LabVIEW interface.

## 4. SUMMARY

A set of hardware and software components have been assembled for the BRF PET accelerator, being commissioned at Fermilab. These components have been used before, but the $^3He$ beam in the environment in which this accelerator sits has proven to be significantly noisier than previous emittance measurements (on H-minus ions and on protons). This is due in part to the close proximity of the RF stations and poor grounding and cabling procedures in the initial accelerator layout. Techniques to deal with this extra noise have been developed and successfully applied to this experiment.

## 5. REFERENCES

[1] P. Young, et. al., "Progress Update on the Development of the 3He Linac for PET Isotope Production". This conference, paper number SPP01.

[2] John Palkovic, "Gabor Lens Focusing and Emittance Growth in a Low Energy Proton Beam," Ph.D. Thesis, U. Wisconsin-Madison, 1991.

[3] "Factors Affecting $H^-$ beam Performance in the Fermilab Linac," by C. D. Curtis, C. W. Owen and C. W. Schmidt, *Proceedings of the 1986 Linac Conference* (Stanford, CA), pp. 138-140.

[4] The IRM is thoroughly documented on the world-wide web at `http://www-linac.fnal.gov/irm`. A conventional reference can be found in *Nuclear Instruments and Methods in Physics Research A* **352** (1994) 189-192, "Use of a small stand-alone Internet nodes as a distributed control system," by R. W. Goodwin, M. J. Kucera and M. F. Shea.

[5] LabVIEW is a copyrighted product of National Instruments Corporation.