## SLUYTERS ET AL: A SINGLE PULSE TRANSVERSE PHASE SPACE BEAM ANALYZER

A SINGLE PULSE TRANSVERSE PHASE SPACE BEAM ANALYSER\*

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Summary. A device is described with which one can measure total and partial horizontal or vertical emittances in shorter than 40  $\mu s$ .

# Introduction

Transverse phase space beam properties are usually measured during many beam pulses resulting in an averaged emittance value. A common technique is the pair-of-slit method as used for in-stance by A. van Steenbergen<sup>1</sup> in which angle limits are determined by mechanical scanning of a slit at different positions of another upstream slit. A more advanced version has been published recently by Vosicki<sup>2</sup> and Allison<sup>2</sup> in which the angle limits are determined by a growing magnetic field; the emittance pattern can be displayed on an oscilloscope within a minute depending on the speed of the slit movement across the beam. A single pulse phase space analysis observes emittance variations from pulse to pulse. This has been obtained by Sluyters<sup>3</sup> using the emulsion technique, which was later refined by Bovet and Regler<sup>4</sup>, who demonstrated the possibility of calibrating the emulsion plates to determine the density distribution within the phase space. A revised version of this single pulse technique is located in the present preinjector of the AGS linac, where it proves to be a useful device in optimizing the preinjector beam instantaneously.

In autumn 1964, G.K. Green of BNL suggested an emittance detector without any mechanical movements, using ferrite sweeping magnets instead of moving slits; such "kickers" were successfully applied in the external beam system of the  $AGS^5$ . This idea has been realized for a 50 MeV proton beam in the inflector region of the 33 GeV AGS machine.

The power supplies of the pulsed magnets were designed and built by E.B. Forsyth and R. Nawrocky.

#### Principle

Figure 1 illustrates the principle of the phase space analyser.

Two identical pulsed magnets with opposite field polarity called "samplers" scan the beam within 10 or 40  $\mu s$  across the first 0.5 mm wide horizontal or vertical slit; the displacement of the beam (input into the horizontal sweep of an oscilloscope) is proportional to the magnetic field.

A third magnet with a 500 kc excitation called the "analyser", scans the beam each 1 us across a second slit in front of a Faraday cup; <u>the displacement of the beam (input into the</u> "Work done under the auspices of the U.S. Atomic Energy Commission. vertical sweep of the scope) is proportional to the magnetic field of the analyser. The grid of the cathode ray tube is connected with the Faraday cup signal, in such a way that the scope brightens only when the cup detects current beyond the level set by a discriminator. The display on the scope is a 500 kc signal representing a transverse phase space diagram.

#### The Magnets

The physical appearance and magnetic properties of the magnets are mainly based on the following requirements:

- a. Double cored magnets for measuring emittances in both phase planes.
- b. 2% uniform field across 25 mm for the samplers and 1% uniform field across 5 mm for the analyser.
- c. If the maximum beam cross section does not exceed 25 mm, a 60 mm minimum gap dimension for the samplers and 30 mm for the analyser.
- d. The lowest possible magnetic field in the gap because the stored energy is proportional to the square of the magnetic field (B) and magnet volumn (V):

$$U = \frac{B^2 V}{2 \mu_0}$$

(in particular important for the 500 kc analyser driver).

- e. A length of the magnet as short as possible for the same reason as (d).
- Ferrite core material with high resistivity for high frequency response.
- g. Installation in vacuum to avoid eddy currents in the metal tubes.

The length and magnetic field for both types of magnets are finally a compromise between maximum expected divergences of the beam, available space in the inflector area and relations between the electrical and magnetic characteristics of the magnet<sup>\*</sup>. The final approximate characteristics for both magnets are summarized in Table I. Parameters for the beam transport system have been obtained with the IBM 7094.

The sampler magnets with 2.4 x 2.4 in. aperture and 6 in. long are made from nickel-zinc ferrite blocks 6 x 3 x 1 in. cemented together. The physical arrangement of the single layer coils (20 turns) is demonstrated in Fig. 2a; they are cemented to the ferrite (see Fig. 2b) which is surrounded by an A1 box.

\*The help of M. Plotkin in this problem is greatly appreciated.

### IEEE TRANSACTIONS ON NUCLEAR SCIENCE, JUNE 1967

The required 2% uniformity of the magnetic field has been obtained within a range of 20 mm. This uniformity and the magnetic field along the axis is shown for both magnets in Fig. 3a and 3b.

The samplers are pulsed by two independent power supplies located outside the tunnel to avoid radiation damage. The supplies are of a condenser discharge type, switched by a hydrogen thyratron. The jitter of the pulse is  $\sim 40$  nsec. The maximum field is about 1900 gauss at 450 amps with a duty cycle of  $4.10^{-5}$ . Figure 4a is a magnetic field time display.

The analyser has 10 turns 1.2 x 1.2-in. aperture and 7.2-in. long is constructed in the same way; the 6 x 1.2 x 3.6-in. ferrite blocks have a higher Q value (~ 20) than those used for the sampler (Q <10). The 500 kHz excitation for the analyser magnet is derived from a self-excited power amplifier. The block diagram of the circuit is shown in Fig. 5. The analyser operates at a duty cycle of 9 x  $10^{-5}$  and drives the magnet at approximately 95 amps, which produces a maximum field of about 400 gauss. (See Fig. 3c and Fig. 4b).

### Mechanical Layout

Figure 6 shows a photograph of the actual device. The magnets, slits, quartz flags for beam observation, beam transformers and Faraday cup are mounted on a 2-in. aluminum plate. The plate serves as a strong back for optical alignment and also forms part of the vacuum chamber. A beam stopper and three glass windows are mounted in the top of the vacuum chamber. The slit assemblies (.8-in. thick beryllium and .020-in. slit width) each with a horizontal slit and vertical slit are used to determine the centerline of the box. All the components are aligned within .005-in. relative to the slit centerline. The slits are positioned by cams mounted on a common shaft. With this method slit positions are reproducible to within .002 of an inch. External pins are mounted on the 2-in. base plate and are used for aligning the assembled box in the machine. The Faraday cup is a beryllium block 1-in. thick mounted on a Mykroy plate. The quartz flags are mounted at  $45^{\circ}$  to the slit centerline. Both the flags and beam stopper are driven by air cylinders (direct drive). All sliding in the assembly are double "O" ring seals with pump out ports. The magnets and beam transformer's vacuum feedthrough are Mykroy disks with brass terminals epoxied in through holes. The assembly is positioned with leveling screws. Two evapor-ion pumps are attached directly to the box (with bellows) and maintain the pressure in the low 10<sup>-6</sup> scale.

#### The Emittance Display

Transverse phase space diagrams on an oscilloscope have been realized by connecting:

 The horizontal sweep with pickup coils mounted in the aperture of the first magnet.

- b. The vertical sweep with a pickup signal
- from a transformer in the analyser drive.
- c. The grid of the CRT with the amplified Faraday cup signal.

The main problem at this stage is to avoid noise (< 10 mV) on the three input signals during the beam pulse, which can be reduced by using filters, gate circuits, careful layout of the cables, etc.

When partial emittances are required, in other words, display of emittances which represent a percentage of the total beam intensity, then this implies more complex circuits. See block diagram in Fig. 7.

Before entering the grid of the CRT the amplified signal is fed into the "threshold". This circuit provides the required grid voltage only when the input signal is larger than a fixed value. The signal from the Faraday cup is gated during the time that it is above the set threshold level. The integral of the output of this gate is then compared with the total non-gated Faraday cup signal. More details of this circuit is described in the appendix.

Some horizontal phase space pictures for several percentages of the beam are shown in Fig. 8. Similar pictures can be obtained for the vertical phase space by exciting the other set of coils in the magnets. As one can observe the beam is focused at the location of the first slit. This has the advantage of small aperture magnets and the emittance value is a simple multiplication of the two half axis  $r_{max} x \alpha_{max}$ , which value can be displayed on a digital voltmeter. This beam configuration has been made possible by including a doublet in the transport system of the inflector in front of the 5° bending magnet.

The accuracy of the relative emittance values is mainly dependent on the variation of the turnon and turn-off times of the CRT grid (see appendix) and the half-width of the Faraday cup signals (~ 100 nsec). Maximum observed inaccuracy is 15%. The absolute accuracy depends on the magnetic field measurements of the magnets: for the samplers this is better than 1%, for the analyser ~ 10%.

#### <u>Conclusions</u>

The instantaneous display of the emittance is extremely helpful for instantaneous linac adjustment and optimum AGS acceptance. In general the emittance is rather constant from pulse to pulse; beam jumping is sometimes 10% of its diameter and emittance rotations can increase the emittance value, measured over many pulses, with a mean value of 15%. Instantaneous display or printing of the pertinent emittance parameters and its correspondent intensity is essential for full profit from this device. With proper location of the beam transport elements the same device can be utilized for a 200 MeV proton beam by modification of the materrial of slits and Faraday cup to 3 cm thick copper.

#### Acknowledgement

We thank H. Kapfer and G. Rackett for their skillful assistance in the assembling of the magnets and the emittance box, W. Livant and W. Goebel for the controls and cabling, R. Dryden and his staff for the installation of the vacuum equipment and control, G. Kiriokos for building the display circuits, and J. Bunicci for building the sampler power supplies.

### References

- A. van Steenbergen, AGS Preinjector Beam Emittance Area and Emittance Area Density Distribution Measurements, Int. Rep. BNL, AvS-2 (1962).
- B. Vosicki, Proc. of the 1966 Linear Accelerator Conf., Los Alamos.
- Th.J.M. Sluyters, Nuclear Methods and Instr. 27, 301 (1964).
- 4. C. Bovet, M. Regler, CERN/MPS/LIN 64-2.
- 5. E.B. Forsyth, The Fast Kicker of the AGS External Beam System, Int. Rep. BNL, EBF-3, (1964).
- J. Millman, T.H. Puckett, Accurate Linear Bidirectional Diode Gates, Proc. I.R.E., 43, 1, 29-40 (1955).

#### Appendix

### Emittance Display Circuits

The output of the Faraday cup is a series of pulses with a repetition rate of 1 MHz. Neighboring beam current maxima, as viewed by the Faraday cup through the second slit, occur at nearly the same deflection angle or at the same intensity of the analyser magnetic field. Since the H-field reaches any level of intensity twice per cycle, the analysed beam has two maxima for each cycle of the 500 kHz analysing field. This is the reason for the 1 MHz repetition rate. The rise and fall times of these pulses depend not only on the emittance of the sample selected by the first slit, but also on the amplitude of the analyser magnetic field. The circuits have been developed to accommodate rise and fall times of hundreds of nanoseconds.

A block diagram of the display electronics is shown in Fig. 7. The Faraday cup output has a distributed capacitance to ground of the order of 20 pF, and it is connected to a preamplifier by a 6 ft. length of terminated 185 ohm coax line. The maximum pulse height developed across the 185 ohm resistance is 0.1 volts for 30 milliamperes of linac beam current. At present we are using a Tektronix vacuum tube preamplifier to bring the maximum signal to the 1 volt level. This amplifier has a bandwidth of 14 MHz. The output of the preamp goes through about 200 ft. of terminated 93 ohm coax to the linac control room. Here, another amplifier increases the signal to the 20 volt level before it is applied to the threshold detector, as shown in Fig. 7. This amplifier has a bandwidth of 12 MHz. The amplifier is isolated from the threshold detector by a unity-gain common base stage. The threshold detector is a 2N2219 transistor with the variable reference voltage applied to the base. The signal is applied to the emitter, and the output from the collector is amplified in two stages, the first of which is a current mode switch. The output stage is a simple common emitter switch with a clamping diode in the collector circuit. There is no regenerative feedback.

The rectangular output pulses delivered to the CRT are 25 volts high and have rise and fall times of 20 to 50 nanoseconds, depending on how rapidly the signal crosses the threshold. This signal is applied to the CRT grid by way of an inverting amplifier intended to facilitate intensity modulation, which is an integral part of the Tektronix Model 647 Oscilloscope. In developing the threshold detector, care was taken to equalize turn-on time (rise time plus delay) and turn-off time (fall time plus delay). To the extent that they are equal, one can compensate for them with a fixed delay network such as a length of transmission line. For the class of signals expected, we found that turn-on and turn-off times varied from 50 to 90 nanoseconds. The main reason for the spread is the variation in slope of the input signal as it crosses the threshold.

The amplifier and threshold detector, described above, are the only parts of the Fig. 7 needed to generate an emittance picture such as the one in Fig. 8. The threshold voltage is read from the dial of a potentiometer and can be expressed as a percentage of maximum signal height. The remainder of the system sketched in Fig. 7 measures the ratio of the integral of that portion of the Faraday cup signal which occurs during brightening, to the integral of all of the current collected by the Faraday cup during the pulse. A 6-diode sampling gate, enabled by the brightening pulses with the aid of a double-ended current mode switch, selects that portion of the signal which occurs during brightening. Total turn-on and turn-off times for this gate are about 20 nanoseconds. The gated and non-gated signals are integrated separately. At present, the divider consists of a null balance system. The integral of total beam current is attenuated until it equals the integral of the gated beam current. The ratio is then read from the attenuator dial.

Type of Magnet	Gap (g) m	Effective Length (ź) m	B <sub>max</sub> ≃ mv θ ∉ Wb/m	Max. Deflect angle (θ) rad.	$NI = \frac{Bg}{u_0}$	Number of turns (N)	Stored Energy $U = \frac{B^2 V}{2\mu_0}$ joule	y Q	Frequency (kc)	Rep. rate pulses/sec
sampler	. 060	.178	. 1922	. 033	9180	20	9.4	<10	10 40	1/3
analyser	. 030	. 2 04	. 0400	.0079	955	10	.11	~20	500	1/3

TABLE ITHE CHARACTERISTICS OF THE MAGNETS



Fig. 1. Principle of Single Pulse Emittance Device.



Fig. 2a. The Magnet Coils.



Fig. 2b. The Coils Mounted in the Ferrite Core.



Fig. 3a.  $B_y = f(x)$  for Sampler.



Fig. 3c.  $B_y = f(z)$  for Analyser.



Fig. 3b.  $B_y = f(z)$  for Samplers.

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Fig. 4a. Sampler Magnetic-Field Time Display. Horizontal Sweep 50  $\mu$ s/cm. The brighter part represents the utilized portion of the field.



Fig. 4b. Analyser Magnetic-Field Time Display. Horizontal Sweep 50  $\mu$ s/cm.



Fig. 5. Block Diagram of the Analyser Drive.



Fig. 6. The Actual Layout of the Emittance Device.



Fig. 7. Block Diagram of Emittance Display Electronics.



75%

Fig. 8. The top row shows vertical emittance displays of a 50  $\mu s$  and 25 mA linac exit beam for resp. 90, 80 and 70% of the total beam intensities.

The bottom photo shows four emittance displays of a 28 mA linac beam; the threshold level is set at 75% of the beam. One observes the fluctuations from pulse to pulse.