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THE IMPROVED BEVATRON AND ITS PERFORMANCE AT HIGH INTENSITY

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W. W. Chupp, T. Elioff, and W. A. Wenzel

August 26, 1965

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ABSTRACT

As a result of the recent major improvement program, the Bevatron has been substantially improved in performance and experimental capability. The successful operation of the new injection system and the addition of considerable shielding have permitted continuous high intensity operation. Performance characteristics, particularly with respect to the operational techniques used for simultaneous experiments, are described. The properties of the new external proton beam, now required for a majority of the experiments, and the plans for further beam extensions and development of additional experimental areas are discussed.

A. High Intensity

The present maximum beam accelerated to full energy at the Bevatron is 5.3×10^{12} protons per pulse, obtained with a 20 ma injected current. Although for normal operations the intensity is held at 2.5×10^{12}, studies of the machine behavior at peak intensities are continuing.

Figure 1 shows the behavior of the accelerated beam versus injected beam soon after completion of the Major Improvement Program[1] in 1963. Both the captured beam (1 ms after RF turn on), and to a larger degree the 6.2 BeV beam, show evidence of saturation with increasing injected current. For some time the accelerated beam appeared to be limited to 2.3×10^{12} protons/pulse. Improvements in the RF system, reduction of noise, and exploration of beam loading effects on electrode structures gave little or no help in increasing the limit. Some increase was obtained by adjustment of the lenses in the inflector system, but most of the improvement seen in Fig. 1 followed adjustment of the magnetic field using the pole face windings. The field was changed in general to provide slightly greater vertical focusing as well as to compensate better for variations in the field near pole tip laminations. Figure 2 shows the beam loss for various injected currents.

It is believed that optimum conditions have not yet been attained because variations in the pole face winding currents are limited by the present power supply. A new power supply capable of pulsed operation is now under test. This will give added flexibility with a higher available current, which can be ramped with the variable slope initiated at any arbitrary time.

The new injection system has been improved steadily since its installation. While normal Bevatron operation requires only 5 to 8 ma injected, sustained operation up to 20 ma is possible. Work is in progress to increase this level to 30 ma, because the curves of Fig. 1 imply that in this way additional beam can be accelerated.

At present beam levels space charge effects are expected to become important. While intensity-dependent instabilities have been observed, it is not clear to what degree – if any – they restrict the accelerated beam. A previous report[2] has described the spontaneous longitudinal bunching after injection; however a transverse instability has since been observed at the same time. Figure 3 shows both instabilities in the difference signal from two vertical induction electrodes with a 17 ma injected beam when the RF is not turned on. Spontaneous bunching occurs ~ 1 ms after start of injection (we inject continuously for 0.5 ms) and decreases ~ 0.7 ms later as the beam strikes the inner radius aperture. The coherent vertical motion of some portion of the beam is apparent. Close inspection reveals that the longitudinal bunch at the revolution frequency is comprised of smaller irregular bunches. The frequencies observed (Fig. 3a) vary from ~ 75 to 60 K.C. This is the difference frequency between the rotation and vertical motion frequencies. Figure 3b shows (2 μ-sec/cm) an expanded portion of Fig. 3a. The large bunch structure has a 1 cm period (~ 500 K.C. = rotation frequency) and the fine structure in the longitudinal bunching is seen within this period. The transverse motion of the fine structure elements as well as a part of the large bunch is seen in Fig. 3a. This abnormal behavior is absent when single turn injection is used to measure the normal vertical betatron

frequency, which near injection produces a difference frequency ~ 30% higher than those measured in Fig. 3a. Scintillation counters stationed near the region of minimum vertical aperture in the Bevatron have not detected evidence for beam losses at these frequencies. The effects shown in Fig. 3 are barely discernible when the RF is turned on, and they seem to vanish completely 3 to 5 milliseconds after injection. Although these effects are undoubtedly related to the transverse resistive wall instabilities observed at other accelerators,[3] they are harder to observe and interpret in the present case.

We have also measured the pattern of beam loss versus time for various fixed vertical apertures. It is observed that, at a given time, the beam survival versus aperture size is considerably different for high beam (15 ma injected) than for low beam (1 ma), particularly during the first 50 ms of acceleration. As shown in Fig. 4, the 15 ma beam not only is larger in size initially but grows faster vertically than the low intensity beam during the period of beam loss. Similar measurements with a horizontal clipper show neither sensitivity to beam level nor apparent growth. A fast (~ 5 milliseconds) in-out vertical clipper will be built to explore this region more carefully.

Operational intensity will continue to be restricted to 2.5×10^{12} protons/pulse until studies of the increasing radioactivity in the machine are completed. Figure 5 shows the residual activity in different areas during the past two years. Preliminary study reveals that in the regions surrounding the external beam extraction magnets, increased activity beyond the present levels might necessitate specialized handling and working techniques. Furthermore, radiation damage apparently has contributed to an insulation failure of the coil of one internal deflection magnet.

B. The External Beam System

The Bevatron external beam extraction system[4] was installed during the major improvement program. The system, as shown in Fig. 6, utilizes an energy loss target and two deflection magnets, each accompanied by a quadrupole, which are plunged each pulse into the Bevatron aperture. The energy loss target is beryllium, 1/2–in. vertically by 1–in. horizontally by 1/2 to 1–in. long, depending on the extraction energy.

The deflected beam is brought to horizontal and vertical foci approximately 25 and 6 ft, respectively, upstream of M_3 inside the Bevatron aperture. The quadrupole doublet Q_3 re–images these at the first external focus, F_1. A fixed collimator C_2 at the Bevatron vacuum exit performs a slight optical purification of the beam. (Less than 1% of the beam is intercepted.) A variable–slit collimator C_1 at the exit of M_2 can be used to reduce the horizontal width of the image at F_1 at some sacrifice of beam intensity. The image at F_1 is re–imaged at the second external focal point F_2, 60 ft downstream, by quadrupole doublet Q4 AB, and again at F_3 by Q4 CD. The normal image size (full width at half maximum) is 0.14–in. vertically by 0.25–in. horizontally at F_1, 0.25–in. vertically by 0.18–in. horizontally at F_2, and 0.1–in. vertically by 0.2–in. horizontally at F_3. A quadrupole singlet can be used with Q4 AB to rotate the image at F_2 through 90° in the event that minimum vertical image size is required at F_2. A similar lens downstream of F_2 can provide a cancelling effect to retain minimum vertical image size at F_3. These singlets have also been used to provide at F_2 a beam parallel (~ 2–in. wide) in the horizontal plane with vertical image height ~ 1/18–in.

Figure 7 shows a beam profile at F_1 with C_1 wide open. The ordinate is the signal from a photomultiplier coupled to a plastic scintillator (1 mm by 1 mm in cross section) which is mechanically scanned both horizontally and vertically. Polaroid film (speed 3000) also is used to measure image size and shape. Because of film saturation the apparent image size depends upon exposure. For use relevant to the measurements of EPB images it has been found that approximately 10^8 protons are required to produce an image size on the film corresponding to that measured with the movable scintillator. Operationally, the monitoring of beam position at each focus uses a plastic scintillator, usually ~ 1/4-in. thick, which can be inserted into the aperture and viewed with a T.V. camera. With the scintillator immediately behind a focus the shadow of a target in the beam is used for precise beam positioning. In this way accurate focusing of the quadrupole elements along the beam channel can be performed easily and quickly. The sensitivity provided is nearly the same as that obtained with polaroid film. After initial tune-up, the operators occasionally check the beam (on a single pulse) via the T.V.-scintillator system. The beam position is sufficiently stable that continuous monitoring by left-right counters is not necessary. During normal operation the T.V.-scintillator is withdrawn to prevent radiation damage and unnecessary background.

The EPB channel is completely shielded, and background is continuously monitored,[5] so that target areas and the final beam stop can sustain intensities up to 10^{12} p^+/pulse. However, to guard against an accidental low energy spill that might be deflected through a positive secondary beam channel, a lead plug (C_3 of Fig. 7) blocks the channel until the Bevatron momentum exceeds the momentum of any secondary channel of the system which

views its source near 0°. Insertion of a heavy beam plug beyond F_1 allows experiments to proceed at F_1 while set-up operations occur at F_2 or F_3.

Downstream from F_1 a second EPB channel has been established. At present this channel provides only a low intensity secondary beam produced at 7.5° from a thin target within magnet M_4A (see Fig. 8). In future operation it will be possible to use M_4A as a switching magnet to provide full intensity beams for this channel. In the immediate future more efficient use of this channel will follow installation of a fast kicker magnet near F_1 to provide deflection of part of the beam onto a thick Channel II target.

Beam-spill methods typically used for internal targets can also be used for the EPB. The extraction efficiency, however, depends upon the method of beam spill. A maximum efficiency of 40% is obtained for those methods in which the spill is controlled by the RF amplitude. Spills using the rapid deflector have lower efficiency because of the introduction of both a time dependent orbit perturbation in the extraction channel and a non-adiabatic deflection which hinders the energy-loss damping of the residual betatron amplitude of the circulating beam. The "string"-spill, which depends on fluctuations in energy loss to produce phase instability, loses beam through nuclear interactions and Coulomb scattering. A new system used for long uniform spills controls the amplitude of the accelerating voltage with a closed-loop system using the rate of loss signal from the beam induction electrodes. This system is particularly useful in flattop operation where the long spiral-in time causes the beam to lose all RF structure. Beam structure from magnet ripple has been reduced by more precise flattop control and by the use of poleface windings to suppress the ripple. The table below gives the extraction efficiencies for the most commonly used operating conditions.

Type of Spill	Spill Length (ms)	Extraction Efficiency (6 BeV)
RF off – normal field rise	~ 2	40%
RF off – 100 MeV/c rise flattop	~ 50	40%
RF off – 10 MeV/c rise flattop	~ 500	40%
RF amplitude modulation	50 – 1000	40%
Energy loss string system	50 – 1000	22%
Rapid Beam Ejection (RBE)	~ 0.25	20%

The external beam intensity is recorded by secondary emission monitors (SEM) which remain in the beam near each focus. The SEM's described elsewhere in detail,[6] are effective in the intensity range from 10^9 to 10^{12} protons/pulse or greater, and the efficiency is independent of the type of spill. In the event that spills for different experimenters differ in time, the associated integrators can be gated. The SEM's operate at pressures of 20 μ or less with a vacuum system isolated within the EPB vacuum system. Hence the chambers can be filled with gas for operation as ion chambers to monitor beam intensities in the range – 10^6 to 10^9 protons/pulse. The upper intensity limit of the ion chamber is of course dependent upon beam duty-cycle.

C. Experimental Operation

The growing experimental program makes increasing demands for simultaneous operation of many experiments. Because the number of experiments that can use the same target is usually limited to two or three, it is important that methods of beam sharing between targets be developed. Not all experiments require full beam intensity. Beam sharing among internal targets, including the EPB energy-loss target can be controlled with adjustment of the radius of targets within the Bevatron aperture. Beam sharing among

external beam targets is controlled by target thickness, beam focal properties and the use of fast or slow kicker magnets.

Division of beam in time is also used for multiple target operation. This method of operation is particularly useful when counter and bubble chambers must be operated simultaneously. Most counter experiments now require flattop operation of the accelerator, and without significant sacrifice of counter spill length a bubble chamber short spill can be produced at both ends of flattop. Another useful application of time division of beam is the provision for parasitic operation with small amounts of beam at energies below flattop energy.

Figure 8 shows the experimental areas as of July, 1965. Operational needs in the face of the growing complexity of the experimental program have been aided greatly by the excellent performance record of the Bevatron, which last year operated during 90% of the scheduled experimental time. Because most experiments now require the EPB, we plan to expand the EPB facilities, utilizing both Channel I and Channel II as primary channels. Thus experiments will proceed in one channel while setups are made in the other. In the event both channels need beam, M_4A is capable of switching beam from one channel to the other within the same Bevatron pulse.

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FOOTNOTES AND REFERENCES

* Work done under auspices of the U. S. Atomic Energy Commission.

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3. M. Q. Barton, G. W. Bennett, J. G. Cottingham, A. J. Enright, J. W. Glenn, J. L. Harris, G. H. Morgan, L. W. Smith, A. Tranis, and R. J. Warkentien, A Summary of the Cosmotron Experiments on the Coherent Vertical Instability, BNL Internal Report MOB-7, November 1963 (unpublished).

4. W. A. Wenzel, Proceedings of the International Conference on High Energy Accelerators, Dubna USSR, 1963, p. 698.

5. K. C. Crebbin, R. Frias, W. L. Everette, and W. D. Hartsough, Bevatron Operation and Development. 41 — January through March 1964, UCRL-11560, July 1964 (unpublished).

6. J. J. Barale, LRL Technical Note EET-929, March 1963 (unpublished).

FIGURE CAPTIONS

Fig. 1 Intensity of beam, captured and accelerated, as a function of injected current.

Fig. 2 Relative beam survival for various injected currents. The time is measured from RF-ON.

Fig. 3 Spontaneous longitudinal bunching and vertical motion of the coasting beam after injection. The ordinate is the difference signal from upper and lower pick-up electrodes. The injected current is 17 ma and the R.F. has been left off.

Fig. 4 Vertical aperture required for large and small injected currents.

Fig. 5 Time dependence of residual radiation activity in different areas.

Fig. 6 Extraction system for the external proton beam. C_1, C_2, and C_3 are collimators, F_1 is the first external focus. Magnets M_1, Q_1, M_2, and Q_2 are plunged into the aperture every Bevatron pulse.

Fig. 7 Beam profile at external focus F_1 with collimator C_1 open. The ordinate is the signal from a plastic scintillator 1 mm by 1 mm in cross section.

Fig. 8 Bevatron experimental areas as of July, 1965.

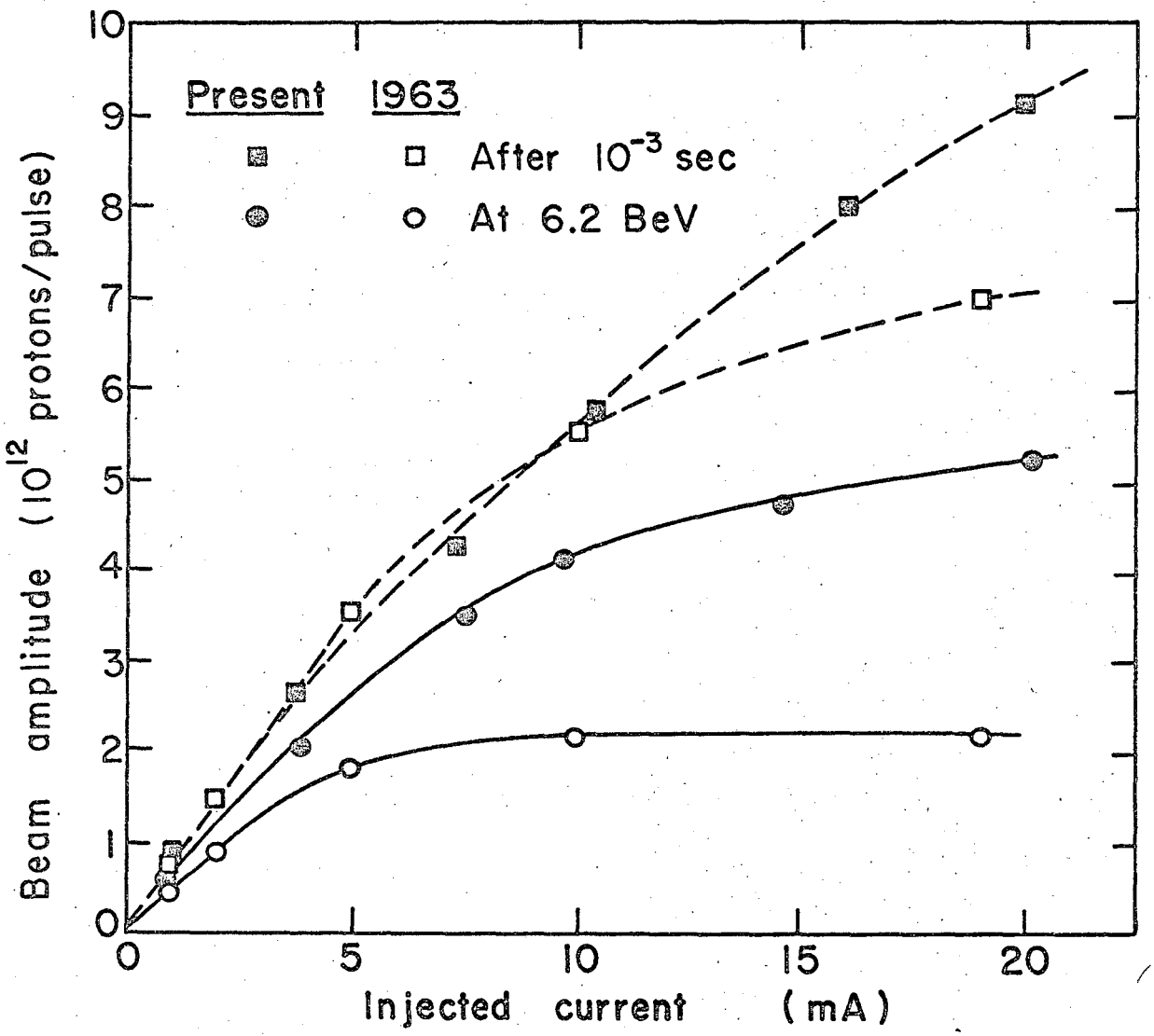

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Fig. 1

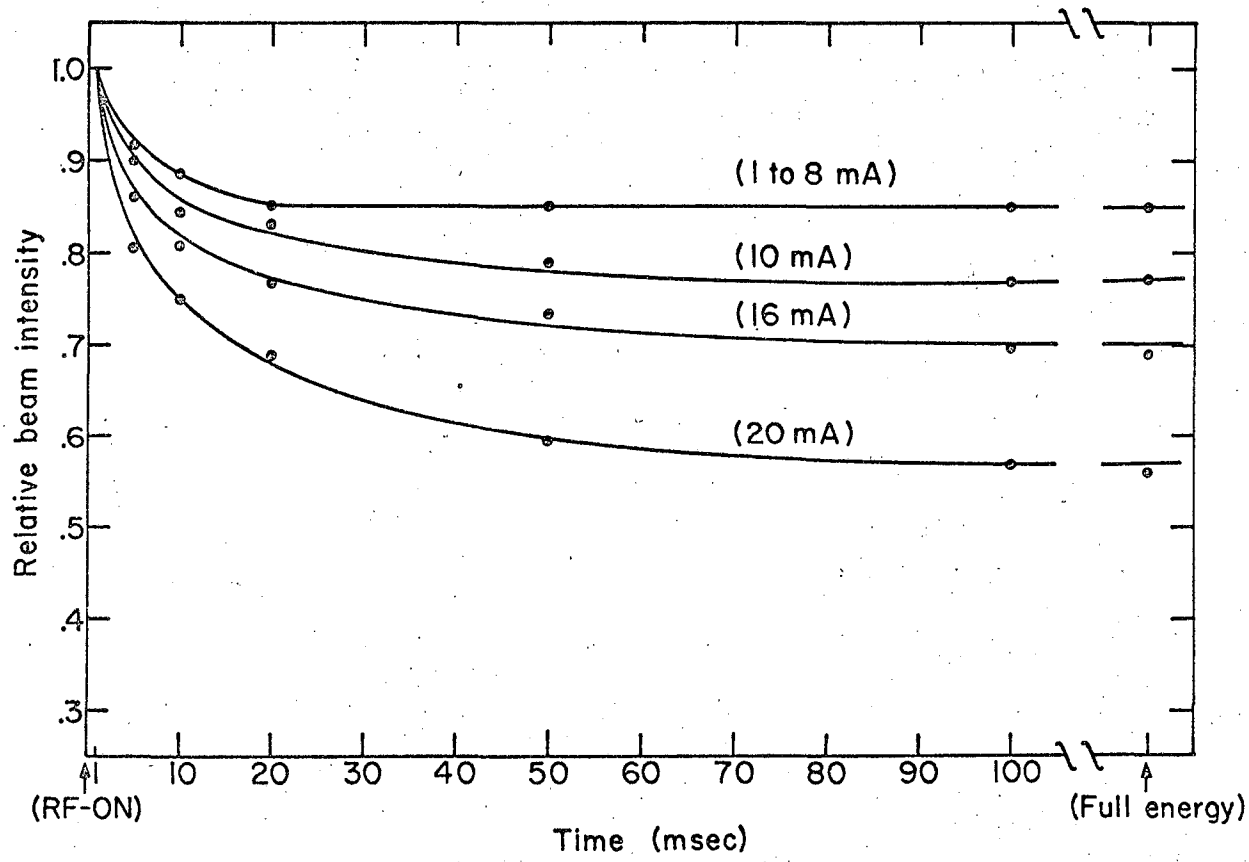

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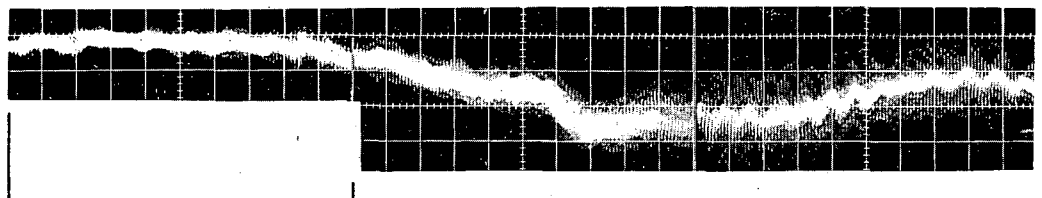
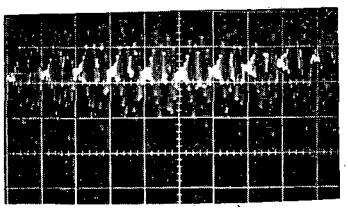
Fig. 2



(a) Sweep speed 20 μsec/cm



(b) Sweep speed 2 μsec/cm

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Fig. 3

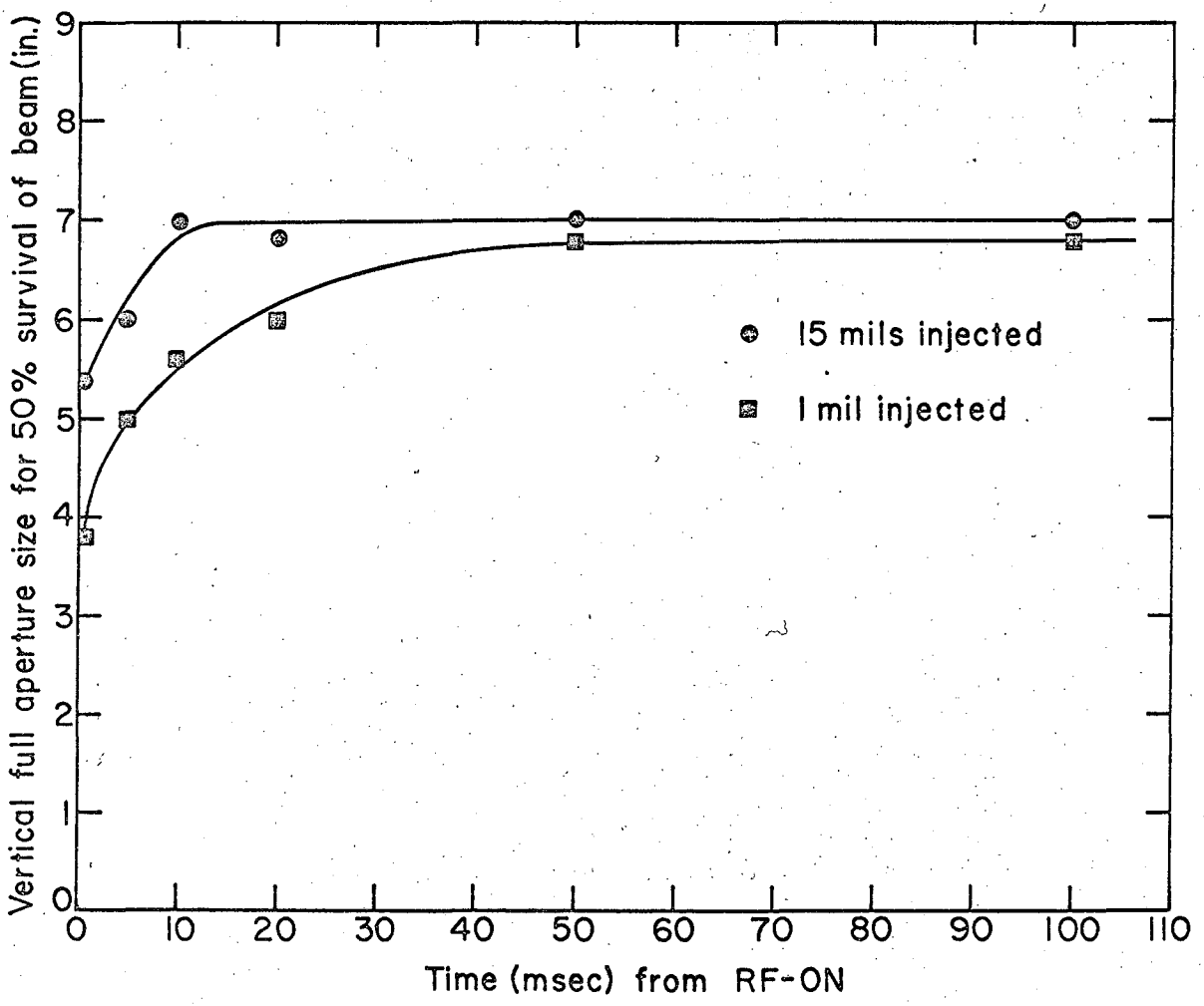

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Fig. 4

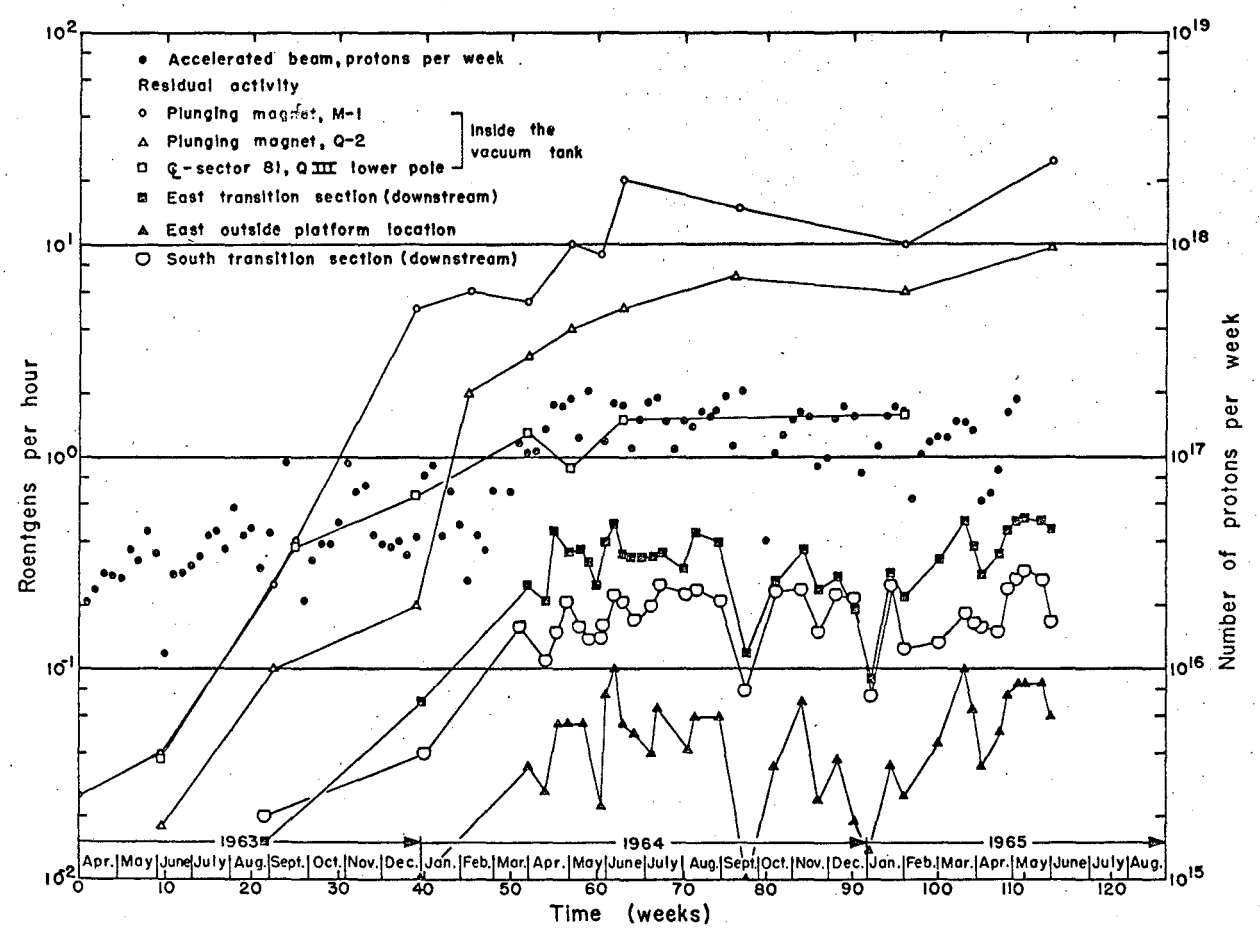

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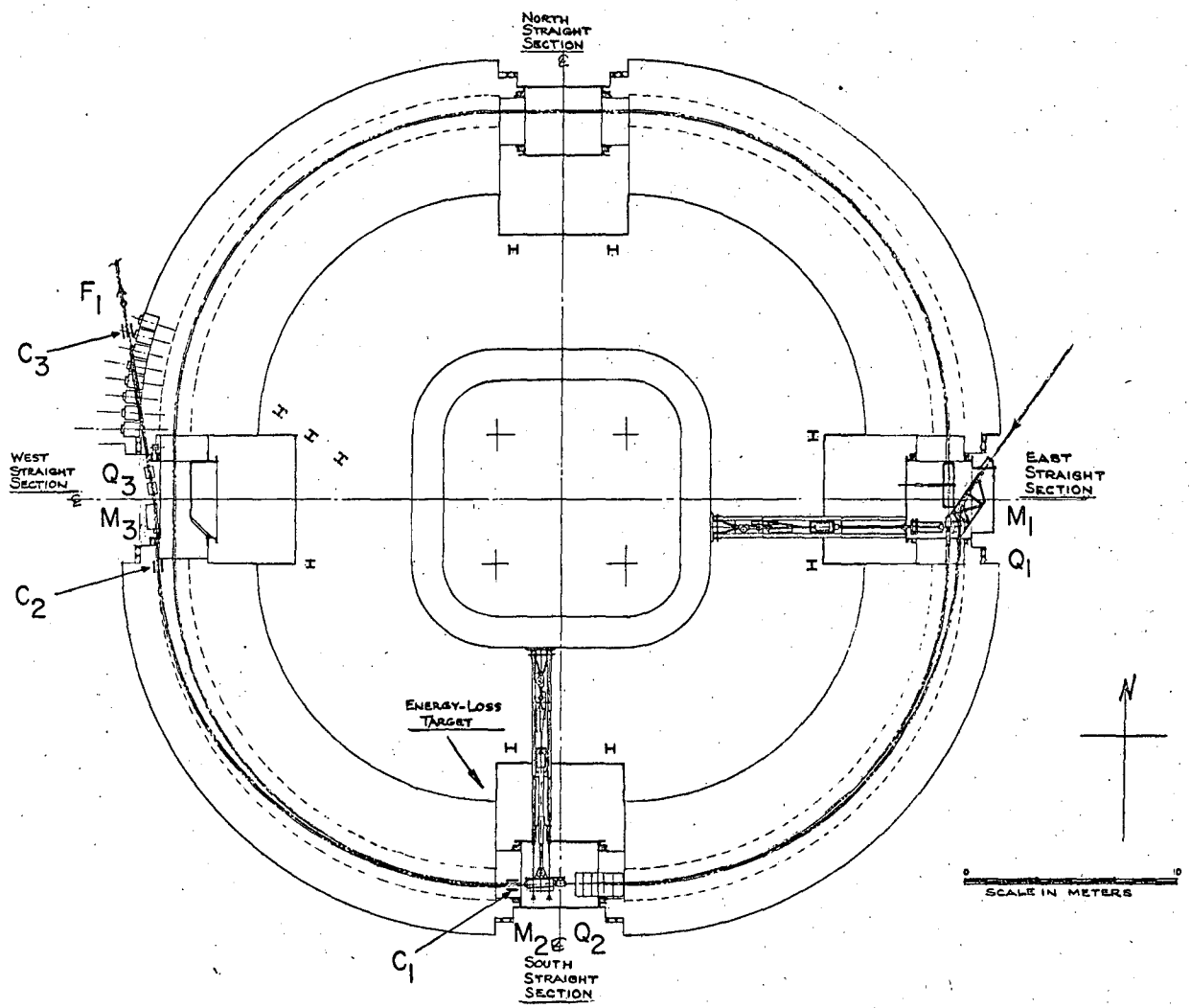
Fig. 5


NORTH STRAIGHT SECTION
F1
C3
WEST STRAIGHT SECTION
Q3
M3
C2
EAST STRAIGHT SECTION
M1
Q1
ENERGY-LOSS TARGET
C1
M2
Q2
SOUTH STRAIGHT SECTION
N
0
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SCALE IN METERS
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Fig. 6

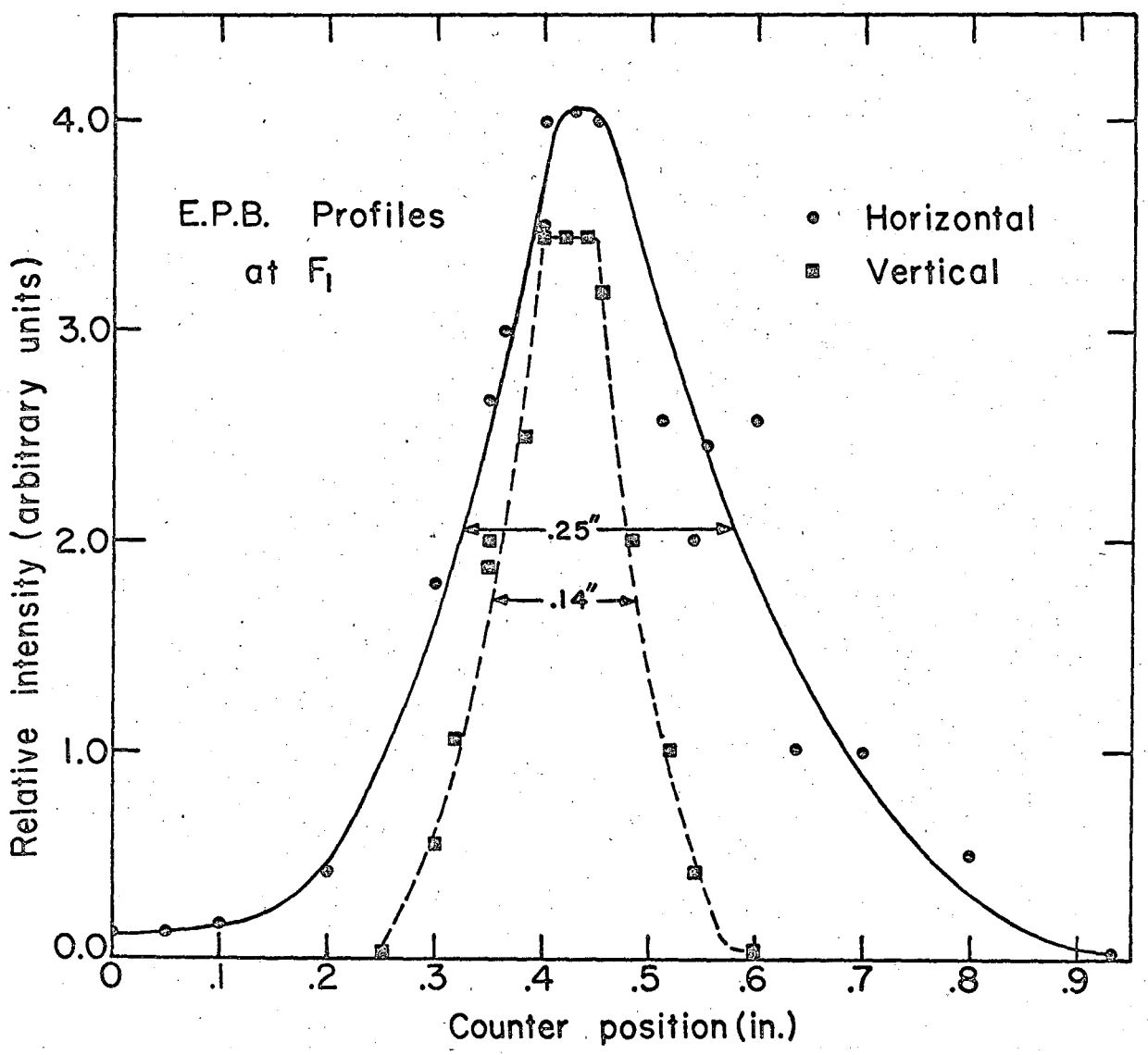

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Fig. 7

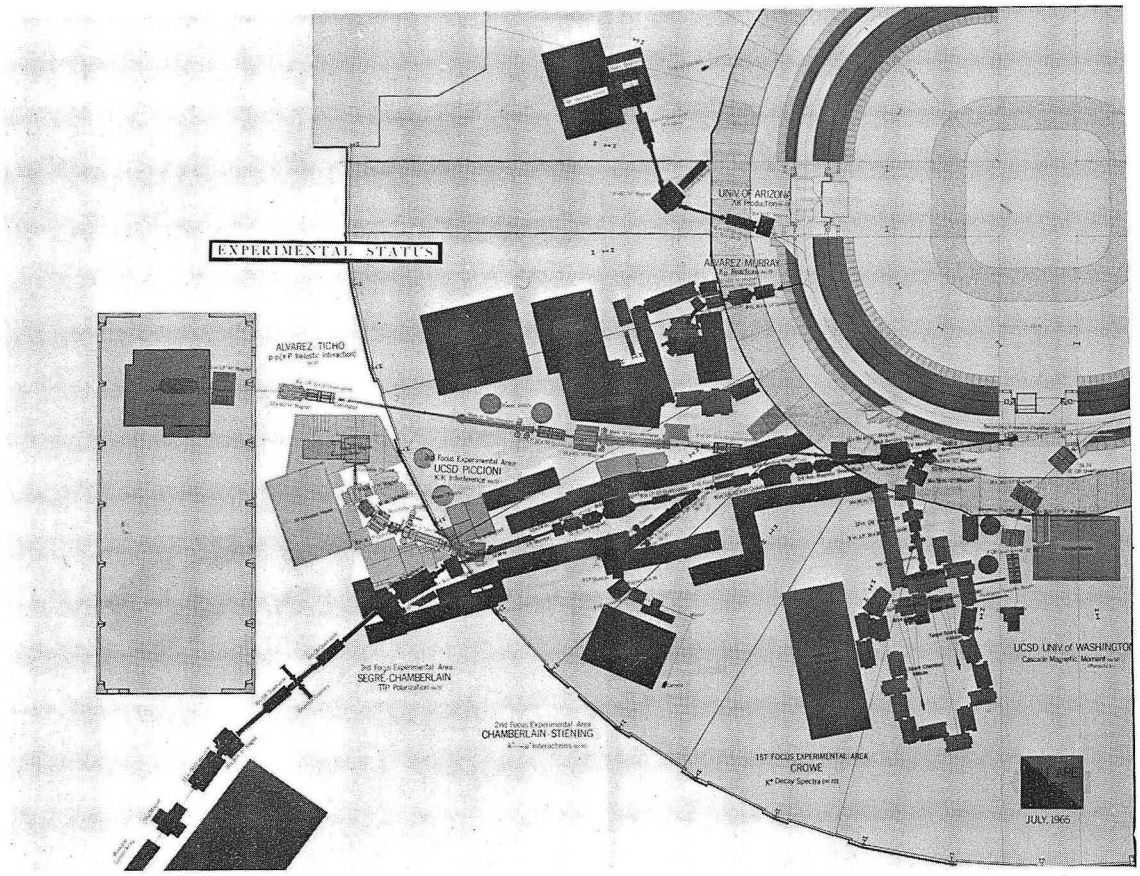
EXPERIMENTAL STATUS
UNIV. OF ARIZONA
ALVAREZ, MURRAY
ALVAREZ, TICHO
UCSD PICCIONI
SEGRE, CHAMBERLAIN
CHAMBERLAIN STIENING
1ST FOCUS EXPERIMENTAL AREA
CROWE
UCSD UNIV. of WASHINGTON
JULY, 1965

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Fig. 8

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