DISCUSSION

COURANT: Your diagram showed that even with the correction the radial field still varied with radius. This should not eliminate the coupling between horizontal and vertical, oscillations, but shift the equilibrium orbit. Have you also attempted to reduce the slope of this curve, so as to make B_r equal to zero everywhere on the machine plane?

KOTOV: In the figure it is shown the radial field component B_r in 4 D-blocks, in which are the correcting coils. In the presence of such a field component in the 4 D-blocks, the mean value of B_r along the perimeter of the accelerator is near to zero and then the coupling between the betatron frequencies disappears.

ZGS PERFORMANCE AND IMPROVEMENT PROGRAM *

L. C. Teng

Argonne National Laboratory, Argonne, Illinois (USA)

The first beam accelerated to about 5 GeV in the Argonne Zero Gradient Synchrotron was reported two years ago at the Dubna International Conference for High Energy Accelerators. Since that time, the ZGS has reached a top energy of 12.7 GeV and a peak intensity of about 8×10^{11} protons/pulse. The ring magnet and power supply have been operating very reliably at a maximum repetition rare or 24 min^{-1} without flat-top or 17 min^{-1} with 250 ms flat-top.

During the shakedown period in the early part of 1964, the most troublesome difficulty encountered was in the vacuum system. The ZGS has a double vacuum system with an outer rough vacuum chamber formed by the magnet yoke and a thin-walled inner high vacuum chamber. Before the vacuum control and protective interlock systems were adequately debugged, some operational error led to an accidental loss of the outer vacuum and collapsed the inner vacuum chambers in three ring magnet octants. A couple of months were spent in repairing these chambers, installing rupture diaphragms, and modifying the vacuum control and interlock logics. The vacuum system has since been in trouble-free operation.

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

Very little trouble was encountered in the operation of the 50 MeV linac injector. The focusing quadrupoles in the drift tubes are still operating in the + — + — mode. The linac normally produces a beam of about 20 mA at a pulse duration of 150 μs and an emittance of about π mrad-inch. Some arc-down difficulties were encountered in the 750 kV Cockcroft-Walton preaccelerator. This was traced to the field distortion caused by the dielectric rods which are used to control the ion source inside the high voltage terminal and which were set right next to the accelerating column and inside the voltage dividing rings. These control rods were moved to a position perpendicular to the accelerating column. This eliminated the arc-down troubles. During part of the ZGS maintenance period, the linac is available for beam studies. We have been studying the dependence of the energy distribution and the emittance on the preaccelerator voltage, the linac r.f. level and flatness, and the buncher voltage and phase. Minor improvements are being made on the r.f. system of the linac, such as the addition of closed-loop feedback circuitry to maintain the r.f. level during beam loading. We are also modifying the preaccelerator voltage regulation system and working on a development program with MURA for a high current ion source and a doubly re-

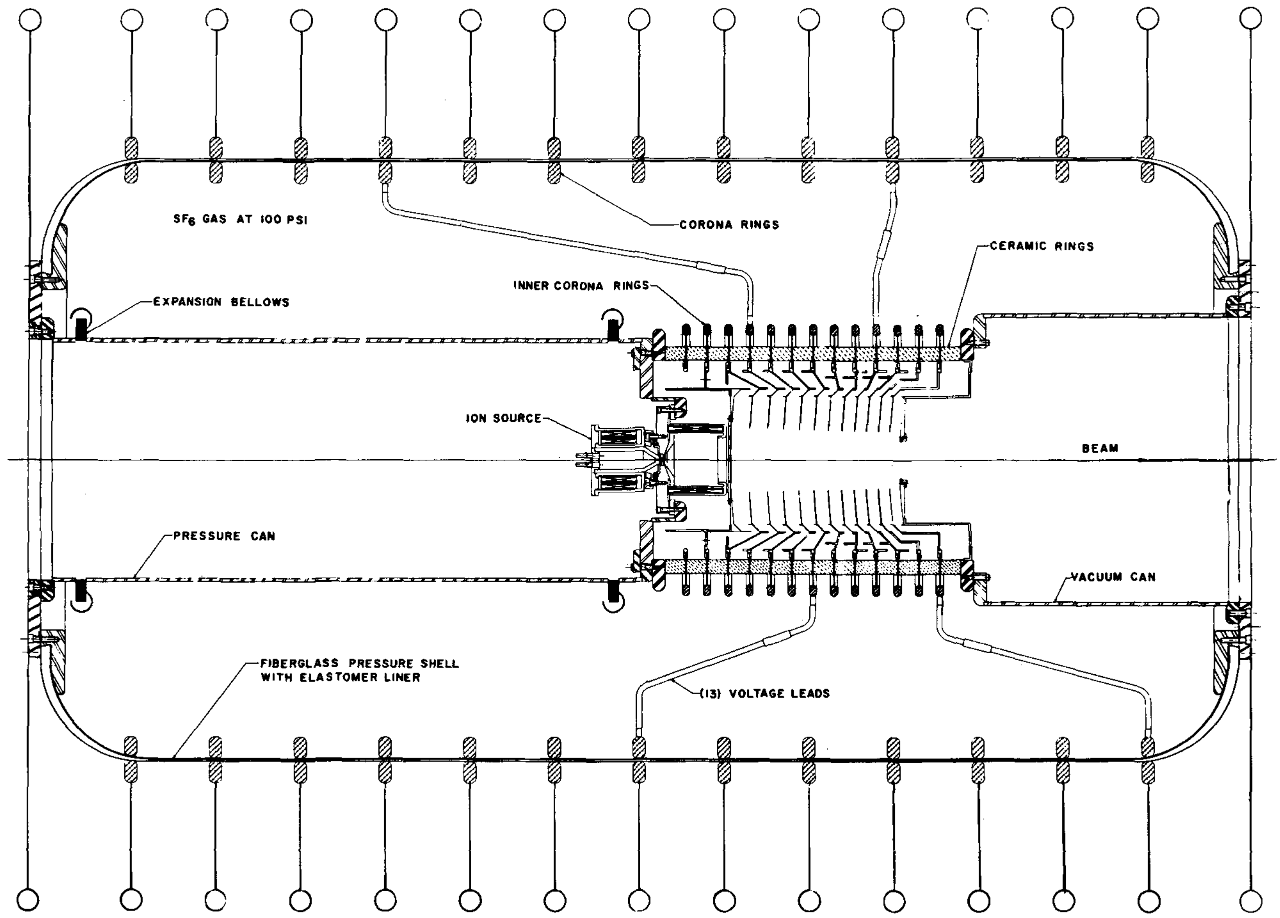


Fig. 1

entrant short accelerating column shown in Fig. 1.

The ZGS is now operated around the clock. In a 3-week cycle, 14 days are used for physics experiments, 4 days for scheduled maintenance and for installation or modification of components, and 3 days for accelerator studies and tuning of new or modified components. During the time for physics experiments, the average intensity is about 5×10^{11} protons/pulse and the average efficiency is about 85 per cent.

The beam behavior in the ZGS during acceleration is as follows: With an injected beam of 15 mA and a useful pulse duration of about 100 μs, we can regularly inject 0.5 to 1.0×10^{13} protons to coast in the ring. About one-third or about 2 to 3×10^{12} protons are captured by the r.f., capture being defined as surviving 5 to 10 phase oscillations. This percentage is fairly close to the theoretical capture efficiency. Because of the eddy currents in the vacuum chamber and in the magnet laminations having a combined e-folding growth time of about 9 ms, the useful radial aperture of the ring magnet is continually reduced until at 20-30 ms after acceleration, the useful aperture is reduced to some 14 in from the full 32 in. A factor of 2 to 3 in beam intensity is lost. At this intensity level of about 10^{12} protons, we encounter regularly total beam loss beyond about 100 ms due to the coherent vertical beam instability caused presumably by the effect of the image charges on the top and bottom of the vacuum chamber. The threshold intensity for the onset of this instability depends on the radial position of the beam in the chamber, i. e., on the radial gradient of the betatron wave numbers. With careful adjustment of the radial position of the beam over the entire acceleration period, we have obtained a peak intensity of 8×10^{11} protons/pulse.

Together with MURA, we constructed and tested a prototype feedback system to damp the coherent vertical oscillation. For the ZGS, where the harmonic number of the accelerating r.f. is 8, such a system is complicated by two fac-

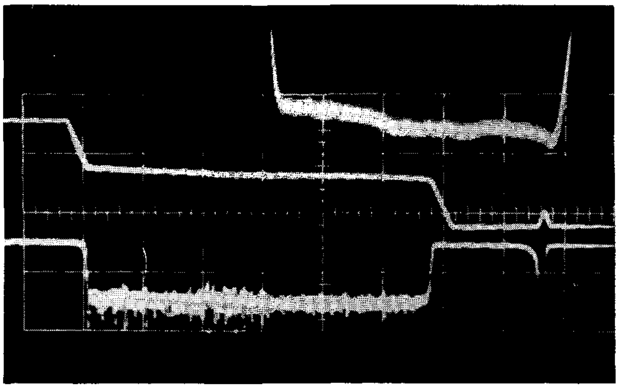


Fig. 2

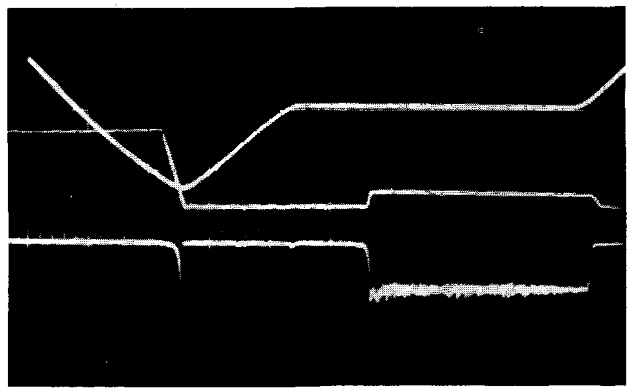


Fig. 3

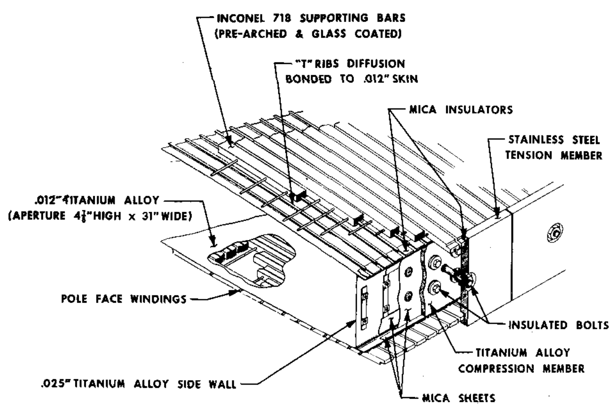


Fig. 4

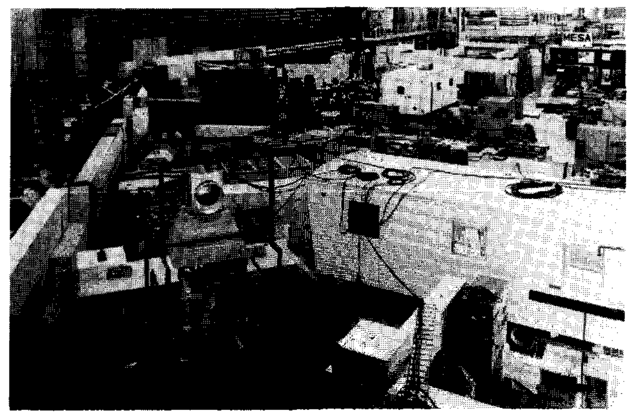


Fig. 5

tors: First, since the oscillations of the 8 bunches of beam are independent in phase, the feedback amplifier chain has to be broad-banded ($\gtrsim$ 50 mHz). Second, the driving voltage obtained from the signal picked up from one bunch has to be applied to the same bunch; hence, the delay time between the pick-up and the driving electrodes, which are azimuthally separated by approximately (integer $\pm$ ¼) betatron wavelength, has to track the particle revolution time. Tests made using the prototype system and artificially excited coherent vertical oscillation show that the damping system indeed behaves as expected. The final feedback system will be installed and put into operation next month.

Since the ZGS ring magnet is not equipped with poleface windings, we fabricated and are installing field-shaping coils to go on the end guards of the ring magnet octants. These will help to widen the useful aperture during the initial 30 ms. With both useful radial aperture widened and the coherent vertical oscillation damped, we exepct to eliminate or, at least, greatly reduce the beam loss after capture.

Many of the accelerator components are now controlled by the computer. A desired mode of operation is coded as a computer program and read into the computer from punched paper tape. Signals are sent by the computer through a matrix to the appropriate cables to produce the desired mode of operation. Several programs may be stored in the memory and successive pulses run according to different programs. Multitarget and multibeam spill operation is now routine. Figures 2 and 3 show two different programs of acceleration and beam spill which can be alternated between successive pulses. The top traces give the beam spill, the middle traces give the radial position of the beam, and the bottom traces give the magnetic field. The sweep speed is 50 ms per scale division. Figure 2 shows a fast spill for a bubble chamber experiment followed by a 300 ms long spill of the remaining beam from another target for spark chamber experiments. Figure 3 shows a 200 ms long spill on a flat-top at 11.5 GeV from one target. The remaining beam is accelerated to 12.5 GeV and fast spilled on a bubble chamber target.

To properly correct for the eddy current field near injection and for the saturation effect near

Fig. 6

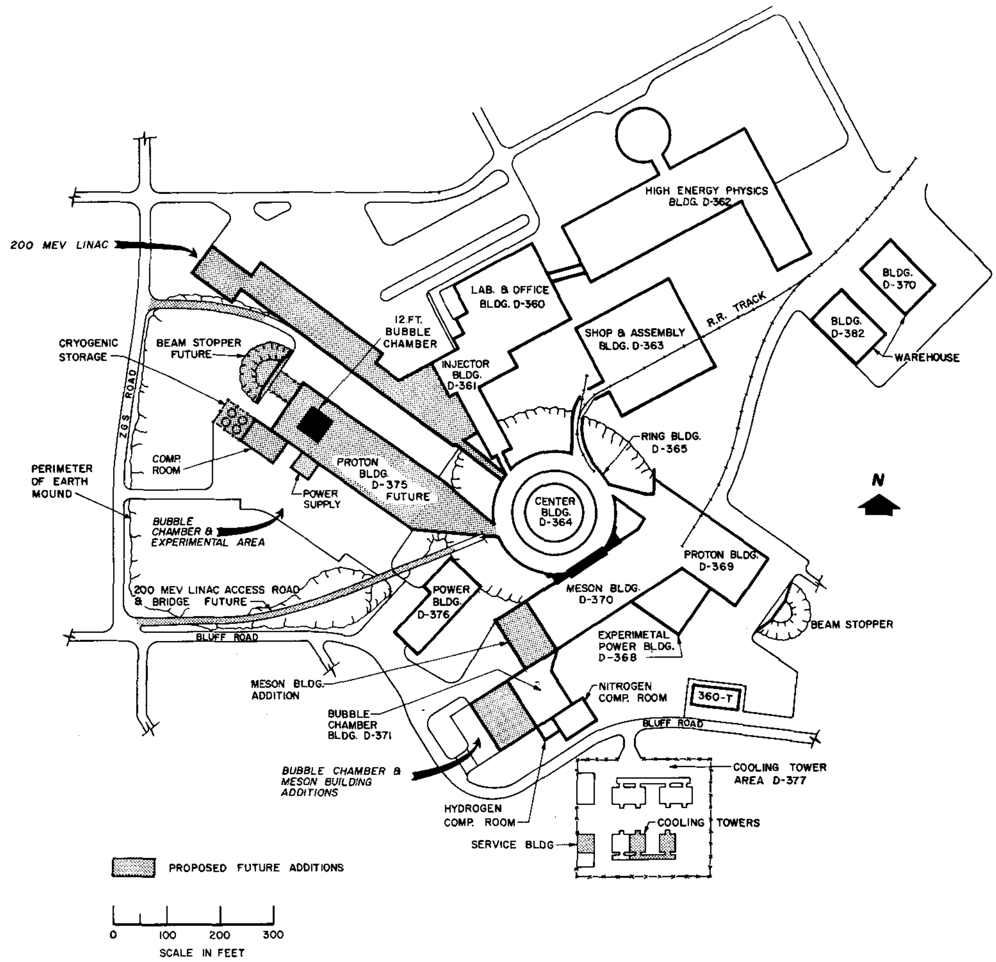
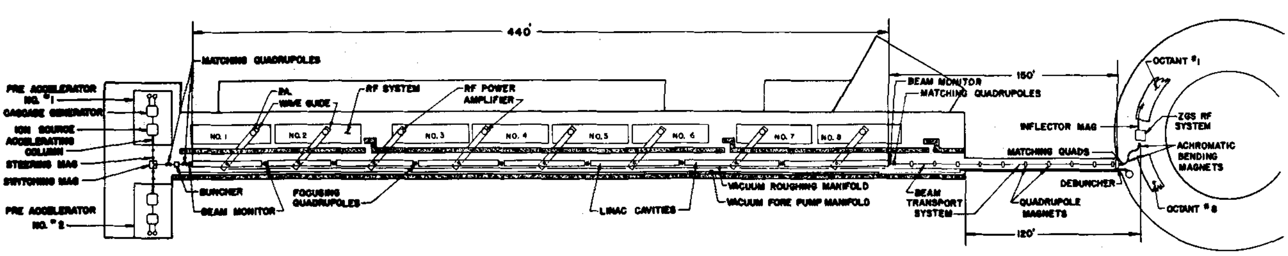


Fig. 7



the maximum field in the ring magnet, we need poleface windings. We are developing a new set of vacuum chambers which will: 1) withstand atmospheric pressure so that we can get rid of the troublesome double vacuum system, 2) be constructed only of metal and ceramic to withstand the expected high radiation dosage, and 3) provide space for poleface windings. The latest technological advances made by the aerospace industry are fully exploited for this application. The chamber will be constructed out of insulated inconel bars running radially to supply mechanical streng (see Fif. 4). The poleface windings will be threaded through holes in the inconel bars and insulated by ceramic sleeves. The vacuum integrity will be provided by a thin (0.012 in) titanium alloy liner which is tied to the inconel bars by radial T-ribs which are diffusion welded to the liner and fit into T-slots cut in the support bars by the electrical discharge milling process. A prototype chamber section is now being fabricated.

The ZGS was so designed that the high energy orbit is radially skewed in the vacuum chamber; hence, the accelerated beam can be extracted by the conventional Piccioni system with fixed extraction magnet. (See " Status of the Argonne 12.5 GeV Zero Gradient Synchrotron ", Proc. Intern. Conf. on High Energy Accelerators, Dubna, USSR,

Fig. 8 - SUMMARY OF 200 MeV LINAC DESIGNED FOR 100 mA BEAM

Cavity Number	1	2	3	4	5	6	7	8
Input Energy-W_i (MeV)	0.7594	20.056	49.649	77.288	104.029	128.688	153.019	176.728
Output Energy-W_o (MeV)	20.056	49.649	77.288	104.029	128.688	153.019	176.728	199.70
β_{in}	0.0402	0.2035	0.3130	0.3826	0.4355	0.4761	0.5107	0.5403
β_{out}	0.2035	0.3130	0.3826	0.4355	0.4761	0.5107	0.5403	0.5648
$\Delta W = W_o - W_i$ (MeV)	19.297	29.593	27.639	26.741	24.659	24.331	23.709	22.87
Cavity Diameter-D (cm)	95	90	88	86	85	84	83	82
Drift Tube Diameter-d (cm)	Various	16 to 15	16	16	16	16	16	16
Drift Tube Aperture-Diameter, a (cm)	1.3 to 3	3	3	3	4	4	4	4
End Cap Curvature R_c (cm)		4	4	5	5	5	5	5
Range of g/L	0.225 to 0.239	0.250 to 0.331	0.330 to 0.384	0.356 to 0.395	0.389 to 0.418	0.412 to 0.435	0.430 to 0.448	0.443 to 0.459
No. of Cells	71	37	28	25	23	23	23	23
Cavity Length (m)	12.90	14.32	14.55	15.26	15.63	16.92	18.01	18.96
Average Accelerating Gradient, E_o (MV/m)	1.89	2.8	2.8	2.7	2.6	2.5	2.4	2.3
Accel. Rate (MeV/m)	1.50	2.07	1.90	1.75	1.58	1.44	1.32	1.21
Power (Theor., no beam load) MW	0.77	1.67	1.87	1.98	1.99	2.10	2.17	2.18
Power (practical with beam load) MW	2.93	5.13	5.19	5.24	5.06	5.16	5.20	5.13

Total length of cavities - 126.55 m; over-all length including intercavity space - 133.55 m
Total r.f. power - 3904 MW

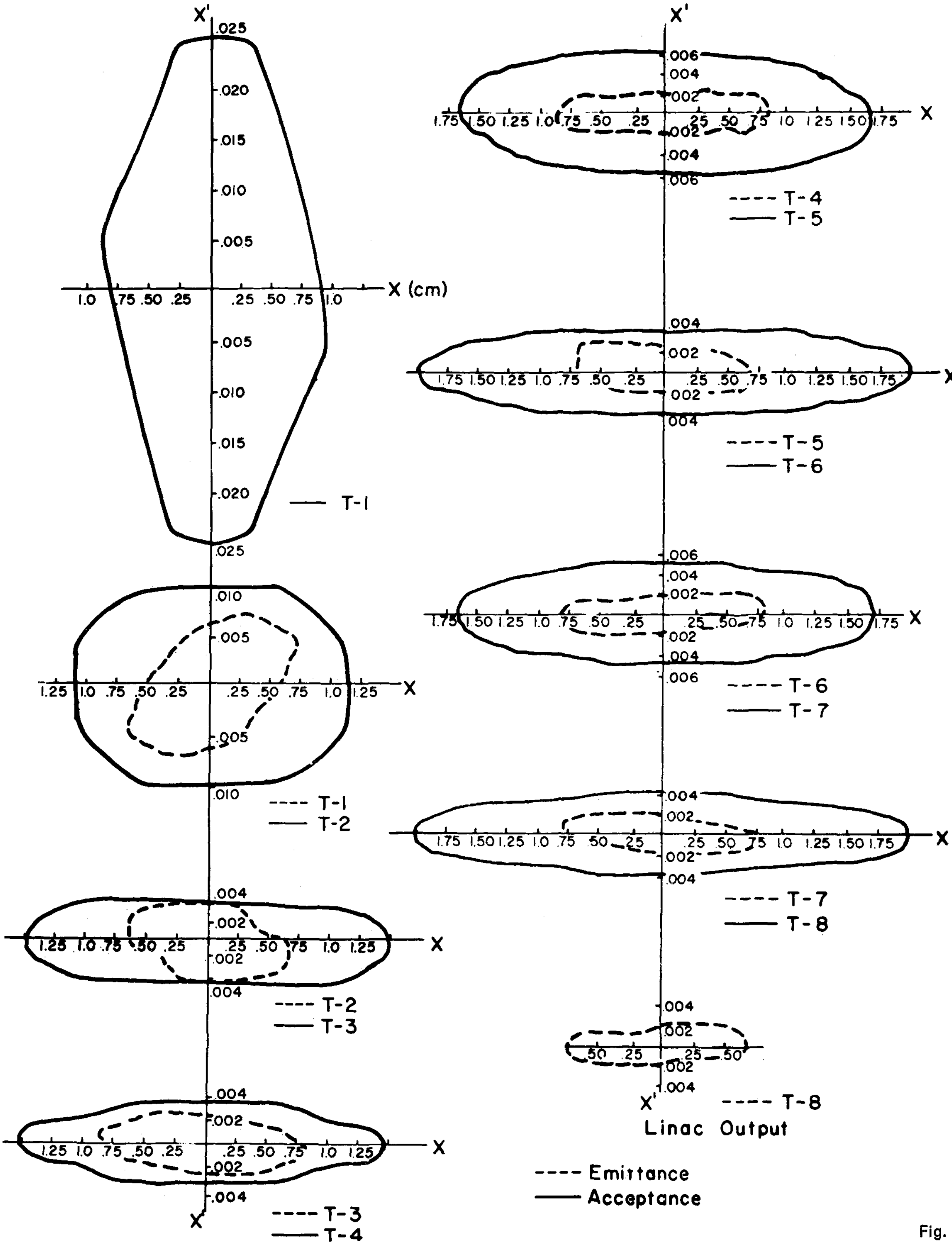

X'
X (cm)
T-1
T-1
T-2
T-2
T-3
T-3
T-4
T-4
T-5
T-5
T-6
T-6
T-7
T-7
T-8
T-8
Linac Output
Emittance
Acceptance

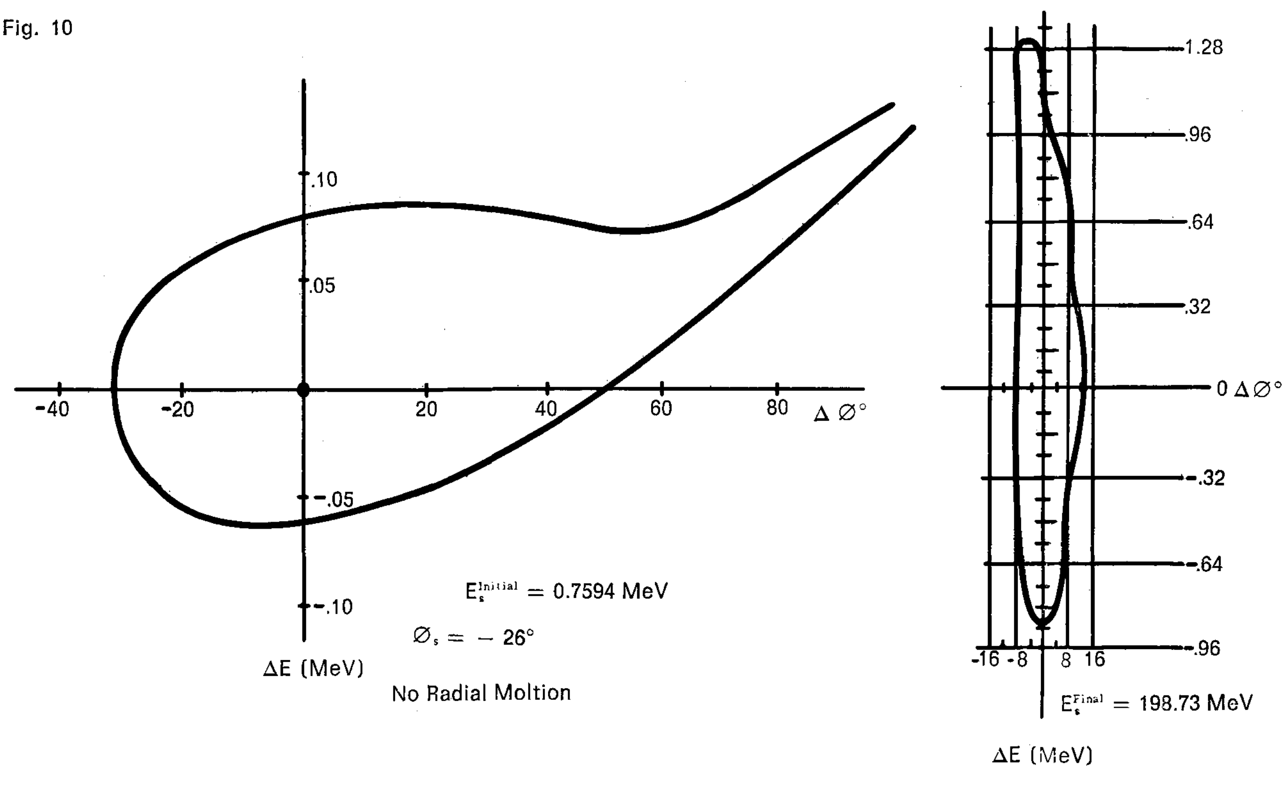
Fig. 9

August 21-27, 1963, pp. 187-196). The extraction efficiency is about 35 per cent.

During the first 15 months of operation, some 11 physics experiments were completed. The experimental floor is, now, rather crowded (see Fig. 5). We have in operation a high momentum electrostatically separated beam which has separated K⁻ up to 5.5 GeV/c momentum with less than 5 per cent pion contamination. This beam is used for a 30-in diameter hydrogen chamber with a magnetic field of 32 kG. In addition, we have a medium momentum (1-6 GeV/c unseparated beam and are installing a low momentum (0 - GeV/c) separated beam. A 40-in diameter heavy liquid bubble chamber has now been tested for operation with both freon and propane. The magnet for this chamber is being assembled and is designed to produce a field of 40 kG. A 10-in diameter helium bubble chamber is now operative with a superconducting magnet producing a field of 42 kG. The extracted proton beam has been used alternately for neutrino experiments with a pion focusing horn and for spark chamber experiments with two targets in tandem: — — a thin one upstream and a thick one downstream. We have in construction at MURA under the direction of U. Camerini and W. Fry of the University of Wisconsin a large cylindrical heavy liquid bubble chamber about 6 ft in diameter and 12 ft long, with a capacity of 7500 liters; and at Argonne under the direction of G. Pewitt a large hydrogen bubble chamber in the shape of a soup bowl with a diameter of 12 ft. Both chambers will be operated in a magnetic field of about 18 kG, and will be used for neutrino and other low cross-section experiments. The feasibility of using a superconducting magnet for the hydrogen chamber is being studied. An experimental building and a second extracted beam is being constructed for this chamber (Fig. 6).

We have completed the study and preliminary design work for an improvement program to increase the ultimate intensity of the ZGS by the construction of a 200 MeV, 100 mA drift-tube linac. The most important contributors to this work are R. Perry, J. Martin, and A. Gorka of ANL and D. Young and E. Rowe of MURA. The

Fig. 10



LONGITUDINAL ACCEPTANCE

LONGITUDINAL EMITTANCE

linac and the preaccelerator are both of conventional design. Figure 7 shows a layout of this linac. Two 750 kV Cockcroft-Walton generators will be used as the preaccelerator so that we will always have a spare to reduce the downtime and for use in the development of the ion source and the accelerating column. The linac is divided into 8 tanks, all excited by triodes of the 7835 type. Except for the first tank where the drift tube shapes in the present 50 MeV injector linac will be used, all other drift tubes will have straight cylindrical shapes. Water-cooled quadrupoles inside the drift tubes operating in the + — + — mode will be used for radial focusing. Figure 8 gives a table of parameters of the 8 linac tanks. Figure 9 gives the transverse acceptance and emittance of each tank. Matching quadrupoles are required only between the first and second tanks. Figure 10 shows the longitudinal acceptance and emittance of the entire linac. This project will include the modification of the r.f. system in the synchrotron ring to accelerate the more intense beam and modifications of the targetry mechanisms and the straight section boxes of the ring for remote handling. Some general and special-purpose manipulators were also designed. We expect that the improvement program will increase the ultimate ZGS intensity by a factor of 5 - 10. As a parallel effort together with MURA, we are further studying and evaluating the present and projected performance of the ZGS, and the beam properties, design, and cost of various types of injectors. This will enable us to determine the optimum injection energy and current, and the accelerator best suited as injector for the improvement program.

DISCUSSION

SEMENYUSHKIN: Which vacuum in ZGS?

TENG: Inside the high vacuum chamber the average operating vacuum is about 10^{-6} torr.

SEMENYUSHKIN: Which time of extraction beam from ZGS?

TENG: Since we use the Piccioni extraction scheme the duration of the extracted beam is controlled by the rate of moving the beam into the energy-loss target and can be varied anywhere from 10 or 20 μ sec to as long as the flat-top, say 300 msec.

WIDERÖE: Have you taken the 10 inch bubble chamber with the super conductive magnet into use?

TENG: Yes we have a 10 inch. He the bubble chamber operating in a superconducting magnet with an 11 inch inner diameter producing a field of 42 kG. The entire system is, now, in operation.

KOMAR: What is the schedule of the improvement programs of your machine? Will the new vacuum chamber be installed together with the new linac or will it be earlier?

TENG: We expect that the new vacuum chamber will be constructed by the end of 1966 and be installed early 1967. Since it will take about 4 years to construct the 900 MeV linac even if we start construction now it will still be more than 2 years after the vacuum chamber. Moreover, the linac project has not yet been approved.

MASCHKE: You inject perhaps 1×10^{13}, and capture $2\text{-}3\times10^{12}$. Then half of this is lost due to aperture restrictions from eddy currents. Aren't both of these losses avoidable?

TENG: The aperture restriction will eventually be corrected by the pole-face winding. As an interim measure we will install field shaping coils on the end-guards of the ring magnet octants. This may produce adeguate correction by itself.

To improve the r.f. capture efficiency we have tried the scheme of having the r.f. on during injection with appropriate rate of frequency modulation and rate of rise of voltage so that we injec tinto stationary r.f. bucket with matched width. Theoretically this should improve capture to close to 100%. Our first attempt showed an improvement of capture efficiency of about 50%.