RECENT OPERATING EXPERIENCE WITH THE ZGS INJECTOR LINAC*

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Machine Reliability

The ZGS Injector System has now been in operation for approximately four years, with nearly three years of injector service to its credit. During this period, its operating efficiency has increased steadily as defective or marginal components were replaced by more reliable elements.

The 750 KV preaccelerator has had no electrical component failures during the last two years, with the exception of some sparking associated with the drive shaft for the power generator in the ion source enclosure. This was a consequence of improper electrical design of the shaft ends which permitted high localized electrical stress to be applied to the paper - araldite laminate, resulting in chipping of the material. The chipping occurred on the inside of the tubular shafting, and it was necessary to cut the shaft in two in order to determine the nature of the problem. Once this was done, it was possible to clean up the chipped areas and recoat the surface with epoxy varnish. A metal shield ring was then placed around the outside of the shaft to remove the high field condition, replacing a dielectric ring used in the original design. The shaft was spliced together at the middle using an inner and outer steel sleeve bonded to the tube with epoxy and doweled for added mechanical strength. The shaft has since been operating satisfactorily except for mechanical wear of the spline at one end, probably resulting from a slight misalignment at the repair joint.

The ion source has operated with only one outage during the last year which was due to a dirty insulating ring. The cathode was not replaced at that time, although it had been in operation for about five months. It is still in operation after a full year on September 21, with 6,343 clocked hours of operation.

The linac rf system has likewise been relatively trouble free, with no serious problems since June of 1965 when a failure of an A-2346 power amplifier tube occurred. This tube had been in operation for 8,400 hours; and when it was opened by the manufacturer, it was found that a broken cathode produced a grid to cathode short. The tube was rebuilt by the manufacturer at about 60% of the then current new tube cost. The tube which was installed in June 1965 had been used by the manufacturer of the rf system during the system check-out and for a short period after installation at Argonne National Laboratory. It has now a total accumulated running time of 10,217 hours, and to all appearances shows no indication of deterioration.

The overall performance of the injector system is indicated by the amount of unscheduled down time chargeable to the system. During a scheduled operating time of 4,690 hours in calendar year 1965, the injector system was charged with 5.07% down time. During the first eight months of 1966, with a scheduled operating time of 3,872 hours, 1.67% down time was charged to the injector system.

Machine Modifications

RF System

The only major modification that has been completed in the injector system is the replacement of the double deck anode modulator for the P.A. This consisted of a series-parallel combination of four ML5682 switch tubes. The initial objective in planning the modulator replacement was to eliminate some inherent difficulties associated with imbalance of the loading of the series-parallel arrangement. It was also expected that some increase in the range of ΔV and of ΔQ from the storage capacitor would be available. The new modulator is a single-deck, one-tube modulator. In conjunction with this project, the closed loop system for linac rf gradient stabilization, of which the P.A. modulator is one element in the loop, has been rebuilt. This system will be discussed in a paper by Joseph Abraham and Richard Castor.

A number of deficiencies in the rf system are recognized and steps are being taken to eliminate some of them as soon as possible.

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Among these are the following: (a) The last stage of the IPA was modified some time ago to improve reliability, but at the expense of power gain. Other amplifier stages are still somewhat unreliable. The IPA chain is, therefore, being redesigned to remove these deficiencies. (b) The present rf power requirement of the linac with 20 mA beam is about 3.5 MW. As demand by the ZGS for more beam will certainly take place, it will be necessary to couple more rf power into the linac; and obviously, the transmission system must be properly matched. Because of having only a short section of waveguide between the P.A. and the linac, reliable rf measurements in the guide are difficult. Consequently, the impedance match between the generator and the load is not easily optomized. Improvements in the instrumentation are being made which will permit more accurate measurements on generator and load characteristics.

Hydraulic Power System for Preacceleration

Mention was made earlier of a problem with the insulating drive shaft which drives a generator in the ion source enclosure. This and other potential mechanical problems inherent in this system suggested the need of a spare generator system. It was finally decided to build a unit in which an insulating fluid would be used as the medium for transmitting power to the high voltage terminal. This system is presently in process of being assembled. It comprises a motor-driven vane-type hydraulic pump which will develop about 1,000 psig, dielectric flow and return lines from ground to the high voltage terminal, and a vane-type hydraulic motor coupled to a 400-cycle generator enclosed in the terminal. The fluid will be a turbine oil which will be kept dry and free of particle by means of a filter supplied with the hydraulic system. The flow lines are of glass-epoxy, made up in about two-foot lengths with metal fittings which will be electrically connected to intermediate voltage points in the high voltage structure. The system will be tested first in a 500 KV system before installing in the preaccelerator.

High Gradient Accelerating Column

The accelerating tube in the Preaccelerator was designed to handle a total beam of about 75 mA. When it is operated at beams of less than about 65 mA, it is possible to produce a good focus beyond the end of the column. However, considerable lens aberration occurs with larger beams, and at the present operating level of 120-140 mA from the preaccelerator, optimum focus conditions are such as to give a diverging beam from the accelerating tube, which becomes more difficult to handle with large current.

Even before designing the existing accelerating tube, consideration was given to the feasibility of holding 750 KV across a short accelerating gap. About three years ago a practical design was developed for such a system, which is now in the construction stage. The accelerating tube is 30 inches long, with a reentrant cone at each end which reduce the accelerating gap to about 6 inches. The anode plate is removable and constitutes the anode of a duoplasmatron ion source. The cathode cone will terminate in a ring of a special material best suited for the application. A tungsten-copper alloy, which has been useful as ion source extractor electrode, will be tried; but titanium or other alloys may be used as experience may dictate. The ion source may inject directly into the accelerating gap without additional extractor electrodes or focusing elements. The field in the first half of the gap is nearly parallel, but by shaping the anode surface other field configurations might be obtained as required for focusing action.

A dielectric pressure cylinder 40 inches i.d. and 60 inches long encloses the accelerating tube and supports it by means of reentrant metal cones from the cylinder ends. Insulating gas at up to four atmosphere prevents breakdown across the accelerating tube.

Along with the new accelerating tube a new or modified beam transport system will be required to match the beam through the buncher and into the linac. The aim is to supply at least 100 mA of protons to the linac and ultimately to accelerate at least 50 mA through the linac.

Variable Energy Debuncher

A separate rf power amplifier system is being assembled to drive the debuncher which, heretofore, has been driven from the linac. Included in this system is a phase-shifting unit which will permit ramping the debuncher phase relative to the linac during a beam pulse in such a program that the mean beam momentum increases during the pulse at a rate which tracks the $\dot{B}$ of the synchrotron guide field, and thus maintains constant radial betatron amplitude in the ZGS. It is anticipated that, since the ZGS captures and accelerates small, better than large, betatron amplitudes, some net gain in captured beam may be achieved. Approximately normal debunching action is maintained in this mode by operating the debuncher at about 25% higher than normal rf voltage.

A recent set of observations on the behavior of the coasting beam in the ZGS shows clearly that when the debuncher is operated in the normal mode, the negative mass instability is very marked. Ramping the beam energy during the beam pulse should increase the energy spread during the beam pulse by a factor of about two, which should remove the negative mass problem. At the same time, the debunching action should reduce the instantaneous energy spread by a factor of about five, so that both the instantaneous spread and the spread throughout the injection period of betatron amplitudes are much reduced.

Experiments

Perturbation Measurements

Investigation of the rf field distribution in the linac using the metal bead perturbation method has been carried out on three occasions during the last year using improved equipment. In the last two studies the CDC-924 control computer was used for reading out and analyzing the data. Most of the equipment improvements were made by MURA personnel. They also developed and tested on a small drift tube cavity a computer program for the IBM 704 computer which was then coded for the CDC computer by Argonne National Laboratory personnel. On the basis of the perturbation measurements, Don Young has made calculations of transit time factors from the gap fields and will report these and other results during this conference.

Perhaps the most significant practical conclusions to be drawn from these attempts to improve the field distribution are the following:

(a) With the existing set of ball tuners in the linac it is not possible to effect in every cell exactly the desired relative gradient, particularly near the low energy end where the ratio of tuners to cells is small. Thus, if ideal cell-to-cell field distribution is required provision must be made for individual cell tuning.

(b) The end-to-end field tilt is easily and predictably obtainable from very small movements of the end walls. The Argonne National Laboratory linac ends at the high energy end in a half cell, with no drift tube attached to the end wall. Adjustments for end-to-end tilt are, therefore, made at this end. An axial movement of about 0.010" is sufficient to produce a change from a flat distribution to a 10% tilt distribution in either direction, presumably linearly, although the linearity of this effect has not been verified.

(c) Setting up the field distribution in an arbitrary manner, within the limits of cell-to-cell feasibility, is possible. However this does not assure that the cavity can be properly powered. In one instance the coupling loop and wave guide tuning parameters were adjusted to what appeared to be a desirable condition, with a different loop penetration than had been used for acceleration, after which the cavity was tuned for normal accelerating tilt, based on earlier experience. In this case as with some others the excitation signal in the perturbation work was through the final amplifier and main drive loop in order to include the effect of the loop on field distribution.

In spite of this, the cavity could not be properly excited to high power levels, and it was necessary to return to a previous set of tuner and drive conditions. One concludes from this experience that the Argonne National Laboratory cavity and wave guide system, and perhaps the P.A. as well, are very intimately coupled, to the extent that they cannot be treated entirely separately as generator, transmission line and load, but must be treated as one interacting system. Consideration is being given to ways of bringing the system into a more manageable state.

Phase Shift Experiments

An investigation of the possibility of measuring phase shifts of the linac rf field due to beam loading has been started. Only one short test of the method has thus far been possible, at which time it was determined that some of the equipment was not functioning properly. However, a brief description of the method will be given and some oscilloscope pictures representing preliminary results will be shown.

The phase detector in this approach is the individual beam bunches coming from the linac, which presumably are in fixed phase relationship with the linac rf field which accelerates them. The phase reference may be any other rf signal of the same frequency as the linac. In normal operation of the Argonne National Laboratory linac, rf drive builds up from a stable 200 MHz oscillator, closely tuned to the resonant frequency of the linac cavity; but before onset of the beam pulse, the system is switched to self excitation. It is, therefore, possible to use the oscillator as a reference signal source. Tuning accuracy, between linac and oscillator, has not yet been established, although it is easy to see, from transient effect at switch over-time, if there is a significant frequency difference.

The system functions as follows:

(a) The linac beam is collected inside the inner conductor of a 3-1/8" coax elbow (90°) which was modified so that the inner and outer conductors end in the same plane which is transverse to the beam direction. The elbow is supported at the end of a short section of 3-1/8" rigid coax (equipped with a vacuum seal) which carries the beam signal out to a Heliax cable, and thence to a wide band cathode ray oscilloscope (Tektronix 519) on which the individual beam bunches are displayed.

(b) The oscilloscope trace is triggered by a tunnel diode discriminator which receives its signal from the 200 MHz reference sine wave.

(c) The vertical position of the scope trace is ramped by a saw tooth signal of about 90 μsec duration so that successive traces during a beam pulse are separated vertically.

Thus if the scope trigger ocurs at a constant rf phase of the sine wave, the beam bunch signals will appear on successive traces at the same horizontal position on the screen, unless there should be a change of phase between the linac rf accelerating field and the reference sine wave, assuming that the beam bunches all have the same phase relation with respect to the accelerating field. Any phase shift due to beam loading or from other causes would appear in the sequence of traces as a horizontal displacement of bunch position which can be measured in terms of the five nanosecond interval between bunches.

Because of the high frequency of these signals, it is almost beyond the capability of any existing equipment to give reliable and reproducible performance. The tunnel diode discrimator, for example, is being pushed a factor of two beyond its rated frequency capability, with a consequent jitter problem in scope triggering. Moreover, during the test run, due to oversight, it was subjected to a larger rf amplitude than it was designed for, which added to the difficulty. Moreover, the discriminator is biased to trigger just above the zero crossing of the sine wave where phase sensitivity is greatest. Consequently, rf noise must be minimized.

No quantitative results have yet been obtained, but the initial test was sufficiently encouraging that the technique will be pursued.

Figure 1 shows multiple trace oscillograph pictures of a 200 MHz sine wave at different sweep speeds.

In Figure 2 are shown in multiple trace oscilloscope pictures impulses produced by individual beam bunches. The horizontal lines in the bottom and top frames were produced respectively before and after the beam pulse interval. Failure of all bunch pulses to occur at the same horizontal positions is due to timing jitter in triggering of successive traces.

DISCUSSION

R. PERRY, ANL

BLEWETT, BNL: It wasn't quite clear to me how you were putting this ramp on the energy. Could you say another word about that?

PERRY, ANL: This represents the rf sign wave in the debuncher. The normal debunching action is with the center of the beam arriving at the buncher at this point (positive zero) in rf phase. That part of the bunch which arrives earlier receives decrease in energy and that which arrives later receives an increase in energy, so the energy spread of the beam is reduced. Now, by increasing the rf amplitude, the phase of the debuncher can be adjusted so that particles of mean energy arrive somewhat earlier in time at the beginning of a beam pulse, thus receiving a decrease in energy. Now, applying a linear advance of the rf phase of the debuncher during the beam pulse will cause the mean energy point to move upward on the sine wave, crossing the zero at the midpoint of the beam pulse interval, and thus resulting in an approximately linear increase in mean energy during the pulse but also preserving the debunching action. The system could be operated in reverse way, of course, to decrease energy.

FEATHERSTONE, Univ. of Minnesota: I think I understood you to say that, at present, the preinjector delivers about 140 mA of total beam and the linac delivers about 20 mA. Could you say how much of this loss is due to undesired components in the beam, and how much is due to beam transport and acceptance of the linac?

PERRY: We have no particular methods right now of measuring the molecular ratio in the beam. We assume our beam is somewhere between 50-70% protons, but this is only a guess. We know that our beam is diverging as it leaves the column; therefore, our beam transport system does not readily accept all of the beam so a major fraction is lost between the preaccelerator and the linac, and is perhaps due to the fact that we have a large beam coming out of the column and the transport system readily accepts it. We get normally not more than 20 milliamps through the linac. The beam entering the linac is normally about 50 or 60 mA, and this again is in part molecular beam in undetermined proportions.

CARNE, RHEL: You gave the linac as taking 3.5 MW. Does this include the 1 MW for beam power?

PERRY: Yes. I should add this is not an absolutely accurate measurement. It is partly based on measurements that are not altogether correlated, but a reasonable magnitude is about 3.5 MW.

TUNNICLIFF, Chalk River: Were the lifetime figures you gave for the rf power amplifiers filament on times?

PERRY: The rf power amplifier had 8400 hr for the tube which resulted in a broken filament strand, and the present tube has had a total of 10,217 at the last report. These are filament on-times.

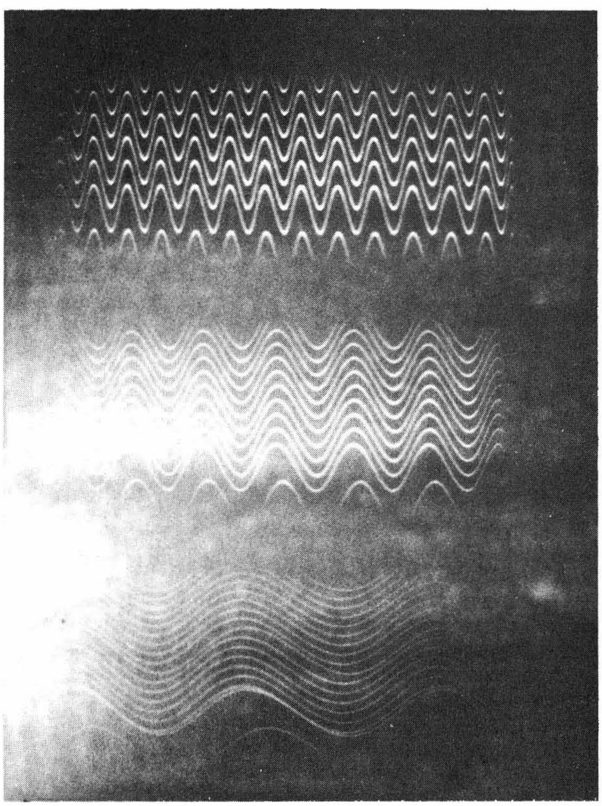

Fig. 1. Multitrace oscilloscope patterns from 200 MHz sine wave.

a. 10 nanoseconds/cm.
b. 5 nanoseconds/cm.
c. 2 nanoseconds/cm.

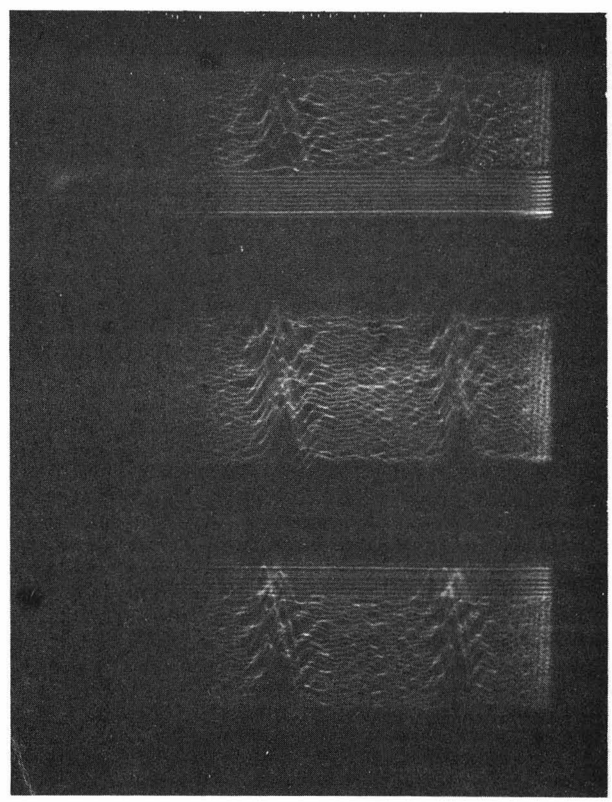

Fig. 2. Multitrace patterns produced by individual beam bunches at 2 nanosecond/cm sweep speed; vertical sweep time, 90 μsec/frame.
Bottom: Beginning of beam pulse.
Middle: Middle of beam bunch.
Top: End of beam bunch.