STATUS OF THE INJECTOR COMPLEX AT LAMPF*

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Abstract

The injector complex at LAMPF consists of two on-line injectors which provide simultaneous H^+ and H^- beams for dual beam operation of the linac. A third polarized ion injector is now under construction and will provide polarized H^- beams. Production runs at LAMPF now employ 100 μA average H^+ beam simultaneously with up to 10 μA average of H^- beam; operational experience and tuning procedures required for dual-beam operation are described. The design of the ion sources, accelerating columns and beam choppers now in operation is reviewed. A discussion of the high voltage problems involved in the operation of these injectors with high duty factor, high power beams together with a detailed description of the engineering of the accelerating tube and of the control circuits and fast protect systems now employed to achieve low fault rates is presented.

I. Introduction

The injector complex at LAMPF has three 750 kV injectors and associated beam transport lines to provide a variety of beams for operation of the LAMPF accelerator. The unique features provided by this system of injectors are high duty factor operation (6% duty factor now operational and capability of 12% operation) and the flexibility to provide simultaneous injection of both H^+ and H^- beams to the linac. This dual beam capability provides two independent beams at 800 MeV for use in different experimental areas. A schematic diagram of the injector complex is shown in Fig. 1.

There are two operational injectors now on-line, which provide high intensity H^+ and low intensity H^- beams. A third injector which will provide polarized ion beams is under construction. At present LAMPF is operating with simultaneous production beams of 100 μA average of H^+ and up to 10 μA average H^- at 6% duty factor (120 Hz with 500 μs pulse duration).

The general operation of the injectors has been quite reliable. During the last three months of production, the accelerator has achieved an on-time of over 80% overall and the injectors have been responsible for only 5% of the total downtime.

II. Ion Sources

There are three ion sources in the injector complex, each source being housed in a separate injector. The H^+ ion source[1] is a high power duoplasmatron based on the Brookhaven design and is capable of 12% duty factor operation at 50 mA peak current. Although production beams at present require only 2.1 mA peak current (100 μA average captured beam), the H^+ injector is being operated at considerably higher (25 mA) peak current with current limiting being effected in the low energy beam transport line. The ion source expansion cup, Pierce anode, and extractor electrode have been apertured to limit maximum current to 36 mA output. This compromise allows the source to be operated in the 20-25 mA range during production runs without excessive violation of the Pierce acceleration conditions and to be operated at design peak current (36 mA) for machine development periods. The original design, 50 mA ion source, will be employed when production beam requirements increase. The ion source has proven to be quite reliable with

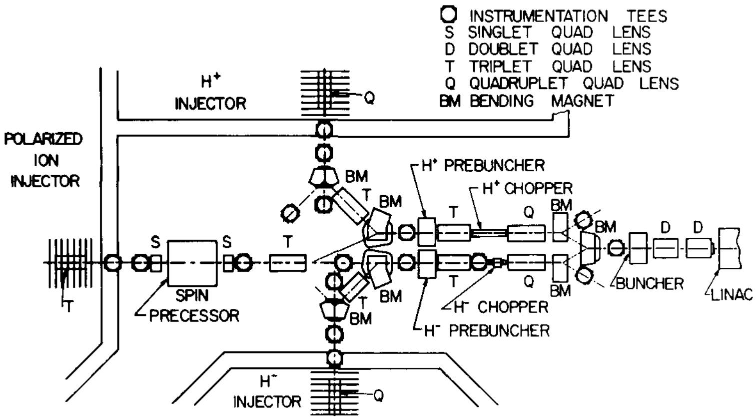

Fig. 1. Layout of the injector complex at LAMPF.

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filament replacement being the major maintenance; filament lifetimes of 3000 hrs can be expected. The source nominally operates with a chamber pressure of 200 μ, a H_2 flow of 1.2 std cc/min, and an arc current of 8 A for 25 mA output.

A modification to the ion source pulsing system was made when a need arose to have the intensity of every tenth pulse attenuated. A circuit to provide this 1-in-10 attenuation was designed, which consists of a suitable resistor, paralleled by a SCR, placed in the line between the arc modulator and ion source. The SCR is triggered through a pulse transformer for each normal beam pulse, thus applying full arc pulser voltage to the ion source. No trigger pulse is transmitted on the 10th pulse and very low arc pulser voltage is then applied to the source on this pulse, thus producing an attenuated beam pulse. A current reduction of the order of 100-200 is obtainable after the first transport bending magnet. The system has been expanded to provide additional attenuation of the low current pulses by using additional pulsing on the H^+ chopper plates (see Fig. 1). This permits the 1-in-10 pulsing mode to supply nA peak current pulses to the linac and, thus, provide up to six orders of magnitude attenuation.

The H^- ion source[2] is a hydrogen charge exchange source and is capable of producing a maximum beam of 1 mA peak at 6% duty factor if pushed. The peak current obtainable is dependent on duty factor and decreases as duty factor is raised, presumably because of the change in molecular species ratio. Normally, the source is operated in the 500-600 μA range which gives component lifetimes of the anode aperture, extractor, and canal electrodes of six to seven months. The lifetime of the anode aperture was greatly increased by using a molybdenum insert, which was pressed into the expansion cup and the aperture opening. The extractor and canal electrodes are fabricated of Ti; part of their failure results from hydrogen embrittlement. If the source were operated at maximum peak current the lifetimes would be greatly reduced at high duty factor operation. The source operating parameters for a 600 μA beam are 4.3 cc/min H_2 flow, dome vacuum of 1.7×10^{-5} torr, and arc current of 12-14 A.

The polarized ion source being constructed is a Lamb-shift source[3] patterned after the sources now in operation on the Tandem Van de Graaff accelerator in the Physics Division at LASL. The Cockcroft-Walton power supply is in operation, ion source components and other equipment are being installed in the equipment dome, and the accelerating tube is being assembled. The source is expected to produce 0.5 μA peak current when it goes into operation early next year.

III. Cockcroft-Walton High-Voltage Generators

Since the operation of LAMPF requires the simultaneous acceleration of H^+ and H^- beams, the requirements on injector voltage stability and measurement are rather stringent. The approach used has been to carry out independent, absolute voltage calibration on the two injectors and to provide a redundant voltage measuring system to insure that accurate measurements of injector voltage are being made. The beams also can be checked with phase scans in the linac, which insure that the beams do, in fact, have the same injection energy.

In order to improve long-term stability in the two on-line injectors, several modifications were made to the Cockcroft-Walton high-voltage generators. The reference power supply was replaced with a digital dial Fluke voltage calibrator which has long-term stability of 0.005%. Precision, low temperature coefficient resistors have been used in the low voltage comparison circuits. The reference voltage has been increased from 170 V to 750 V. Finally, a surge inductor was designed to compensate for the rolloff of the frequency response on the compensated voltage divider leg and has been installed between this leg and the slow stabilizer to protect the low voltage components from spark damage.

The most precise measurement of the voltage is carried out on the compensated voltage divider and 0.01% precision is easily obtained. The compensated divider constitutes one leg supporting the equipment dome and consists of five sections of wirewound resistors provided by Haefely. Each section has a nominal impedance of 425 MΩ shunted by 2000 pF in series with 87 Ω. A spare section was measured by the National Bureau of Standards and then used to calibrate all the sections of the H^+ and H^- compensated dividers at their normal operating voltage. The compensated dividers are inside the slow control loops, but as long as there is no malfunction in the divider, its reading is the real injector voltage. However, this reading will always agree with the reference voltage as long as there is adequate gain in the control loop even when there is a malfunction in the compensated leg, so a redundant measurement is desirable. There is a second independent voltage divider (which is uncompensated) that can also be used to measure the equipment dome potential. Unfortunately, it is not as precise a measuring tool (and in fact was not designed to be so used) since it is subject to temperature and voltage drifts, and in practice it is necessary to allow the reading on this voltage divider to stabilize and then note deviations from the stabilized value.

Two other checks can be made to ascertain if the two injectors are indeed calibrated and operating at the same potential. The equipment domes can and have been connected together; then by running one supply, it is possible to compare both dividers. Prior to the calibration of the divider network utilizing the NBS calibrated section, the domes, when tied together, differed by 0.29% pointing out the need for better calibration. As indicated previously, phase scans of the H^+ and H^- beams in the linac can be used to check if the same energy is being employed.

The Cockcroft-Walton power supply for H^+ acceleration operates at 750.0 kV; its control system is illustrated in Fig. 2. Beam operation requires peak currents out of the column in the range of 15 to 35 mA with a maximum repetition rate of 120 Hz and 500 μs pulse width. To minimize the voltage droop on the dome during the beam pulse, charge is supplied by the bouncer circuit through the center leg of the symmetric cascade rectifier. Observation of the dome voltage droop and ripple is available through the use of a capacitive voltage divider. This divider is

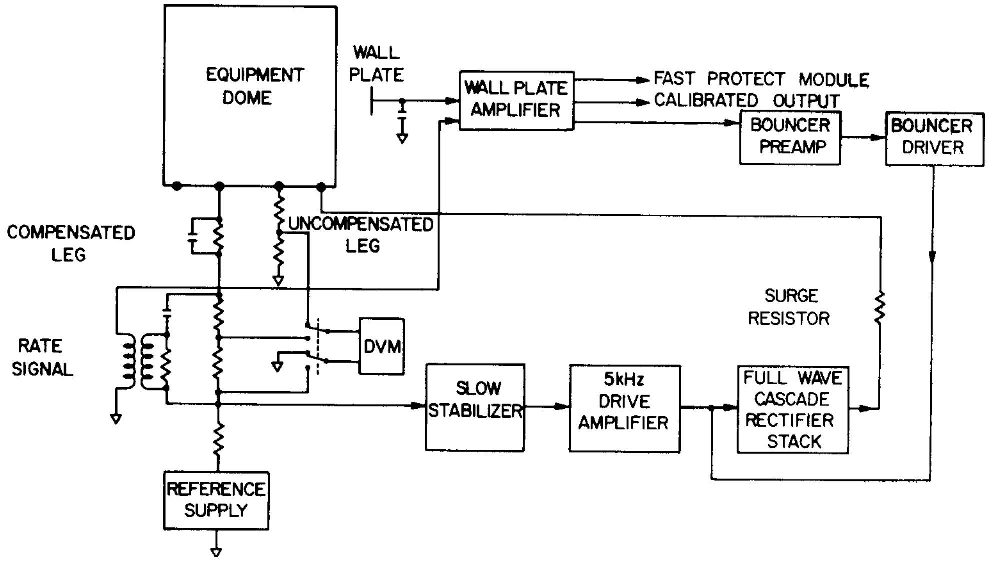

Fig. 2. H$^+$ Cockcroft-Walton control circuitry.

formed by a wall plate capacitor unit; one capacitor of the divider is the capacitance between the side of the equipment dome and a 46-cm diameter plate mounted on the wall of the Faraday cage. The other capacitor is a series capacitance connected between the wall plate and ground across which is taken the voltage signal.

A wall plate amplifier is connected across this capacitance divider and serves a multiple purpose of providing a calibrated output to the control room and to the fast protect module, which shuts off the ion source if the voltage droop exceeds a preset value. For these two functions the input is the voltage provided by the wall plate divider termed the proportional signal. The other section of the amplifier board constitutes the bouncer control preamplifier. In this section the proportional signal is mixed with the rate signal from the compensated leg, forming the input to the Haefely C-W bouncer circuitry. Calibration of the wall plate amplifier is accomplished by applying a 100 V square wave to the dome. The measured 5 kHz ripple on the dome ranges from 30-50 V P-P. The beam droop can be maintained flat in the range of 100 to 300 V over the full 500 μs beam pulse.

IV. Accelerating Columns

The same basic design of accelerating columns is used on all three injectors at LAMPF. The accelerating tube is held between two cones with an intermediate bellows and kept in compression by means of a large transparent Lucite cylinder. Different sets of electrodes are used within the accelerating tube depending on the peak currents to be accelerated and thus, on the ion source employed.

In general, the accelerating columns have operated as expected. On the H$^+$ injector, however, it was found that with the initial design of the accelerating electrodes, the arcdown rate for the design currents was dependent on duty factor (primarily repetition rate) and was unacceptable for high duty operation. The arcdown problem was investigated in detail and a number of changes were made both in the accelerating column and in the Cockcroft-Walton generator to eliminate this problem. No problem has been experienced in the low peak current operation employed in the H$^-$ injector, which operates at the same duty factor.

In the original design of the H$^+$ accelerating column, an exact Pierce geometry[4] was used with electrode apertures only slightly larger than the design beam. It was found that these apertures were too small for real beams and beam impingement damage was found on most electrodes. Part of this damage was due to an operation with misaligned beams produced when an extraction insert melted. It was decided to redesign the electrodes with larger beam apertures and to use an electrode at each voltage subdivision point of the accelerating tube as shown in Fig. 3. Electrostatic calculations were made to check the effects of increasing electrode aperture and the sufficiency of the number of electrodes employed. As expected, the major deviation from Pierce condition occurs in the extractor region and a compromise design employing a smaller extractor aperture was used. The final design employs 15 Ti electrodes instead of 9, and the electrode aperture has been increased from 2 cm to 4 cm diameter.

In order to preclude any possible damage to the accelerating tube electrodes, current sensors have been installed in the voltage dividing network, and error signals due to any beam impingements are tied into the fast protect system and turn off the ion source. In practice, ion source tuning is no longer critical with the larger electrode apertures and these fast protect channels are usually only tripped when large errors in ion source tuning are made or when power supply failures occur.

The time required to high voltage condition the accelerating column after venting has been considerably reduced. This is accomplished by venting

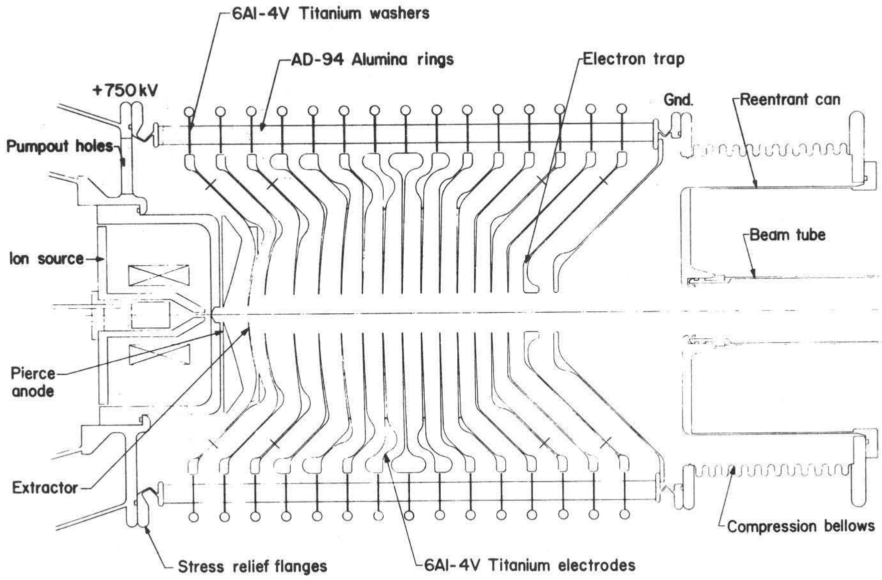

Fig. 3. Layout of the new accelerating tube.

to argon in place of nitrogen as had previously been done. If a flow of argon is maintained during the period the system is open to the atmosphere, the beam can be running at full duty at the operating voltage of 750.0 kV within several hours at a low fault rate. This is in contrast to venting the system to nitrogen and opening to air where it is found that after pump-down high voltage conditioning can be regained within minutes, but that several days are required to obtain the same low fault rate at high power operation. High current operation with the tube indicates that vacuum contaminants do indeed play an important role in fault rate.

The accelerating tube consists of an array of 15 thin 6Al-4V titanium-alloy rings bonded between 16 alumina-ceramic rings with stress relief flanges also of 6Al-4V titanium bonded at both ends. The alumina rings are 34.93 cm i.d. x 38.74 cm o.d. x 3.10 cm thick with 30 μ-in. finish and the titanium rings are 33.02 cm i.d. x 40.64 cm o.d. x 0.064 cm thick, buffed to an 8 μ-in. finish. The stress relief flanges have an axial length of 2.86 cm with a 0.12 cm thick single convolution to reduce stress transmitted from flange bolt-down to the adhesive bond.

Polycarbonate was chosen as the adhesive because of its low outgas rate in vacuum, high tensile strength and low creep rate. A 6% by wt solution of Lexan 145 polycarbonate was prepared in a solvent mixture of 50% methylene chloride-50% 1,1,2 trichloroethane and was sprayed on the ceramic rotating on a turntable for uniform coating. The methylene chloride provides the high solubility and the 1,1,2 trichloroethane reduces the evaporation rate sufficiently to allow spraying. Four coats were applied to each ceramic surface with drying between coats to produce a total polycarbonate thickness of 0.1 mm. No polycarbonate was applied to the titanium rings or relief flanges.

The parts of the accelerating tube were assembled inside a walk-in oven around a 3 post titanium jig, as shown in Fig. 4.

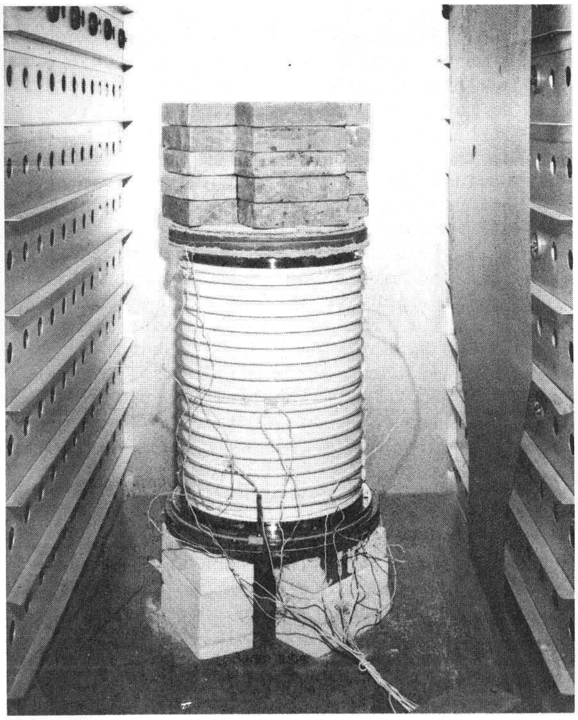

Fig. 4. Assembly of accelerating tube prior to bonding.

Thermocouples were attached to the ceramics in several areas for monitoring temperatures. Lead bricks were used to produce 20 psi loading on the bonds. Provision was made to keep the top flange from rotating when the polycarbonate becomes fluid. The assembly was heated at 0.8°C/min, then allowed to cool at 1.5°C/min.

Temperature uniformity and control are extremely important requiring the use of diffusers. All bond areas should reach at least 240°C to insure bonding, but should not exceed 255°C for any appreciable time or degradation of the bond will result. Furthermore, higher temperatures for any length of time results in the growth of voids in the bond area, which can cause vacuum leaks.

After bonding, the accelerating tube was strength tested at three times normal loading with a 109 kg cantilever load at 20° arc increments. After removing all polycarbonate flash with methylene chloride, the tube was cleaned by grit blasting with 240 grit alumina and wiped with alcohol to remove all grit. The tube was mass spectrometer leak tight when bagged with helium for 5 minutes.

Observations were made of the arcdown incidence of the H^+ injector, and at 6% duty factor and 20 to 25 mA peak beam, they numbered about 5/hr. The risetime of the arc current was 3 μs, and the effect of this fast risetime on the arcdown rate was questioned. The present arc modulator utilizes SCR devices and pulse shaping is not easily achievable. To obtain a slow risetime of the arc, a permalloy tape wound inductor was placed in series with the modulator output to the ion source.

The inductor was tapped at several points on the winding to obtain various risetimes. An inductance of 412 μH was selected for use, and provided a risetime of 36 μs for 10-90% of peak current. Without the inductance the injector would arcdown repeatedly after the first fault, often making it difficult to restore operation even without beam current in the column. Utilizing the inductance and slow risetimes reduced the arcdowns to less than 0.5 arc/hr, and it was noted the high voltage could be restored without these repeated faults.

An additional benefit gained from the use of the slow risetime was an improved performance of the RF systems. The slower risetime permits the RF amplitude controllers to operate optimally. In fact, it has so improved this phase of the linac operation that it has become the standard mode of operation. Operational time has not been available to run without the inductance to once again make comparison measurements. Operation with the slow risetime has resulted in periods up to 24 hours with no arcdowns, and the average number is still less than 0.5 arcs/hr.

Certainly, the column is not tuned for optimum transmission of a slow rising pulse. The extractor voltage is adjusted for maximum peak current; a small amount of beam spill is observed in the initial section of the transport line during this turn-on transient. When an arcdown occurs, it is likely it will be followed by one or two more; the column will then go for several hours with none. The inductor providing the slow risetime has been used in continuous operation since tests were carried out 7 months ago. It has not really been established that the present low fault rate is entirely due to this modification, since there has been a long high voltage conditioning period with high beam power operation. Perhaps, after this long conditioning time for the column, a much lower arcdown rate would be produced even without its use.

It is desirable from an operational standpoint for the injector to automatically resume normal operation after an arcdown has occurred. A system has been installed which provides automatic recovery of high voltage and beam after such faults. Upon receiving an input signal indicating a fault has occurred, the system clamps the 5 kHz oscillator to zero, grounds the input to the slow stabilizer and bouncer preamplifier, and inhibits the beam gate. It then restores operation in the proper sequence. If three arcdowns occur in less than one minute, the system requires being reset by an operator. By sensing the arcdown and immediately clamping the 5 kHz oscillator to ground, the slow stabilizer is prevented from tripping the anode current overload circuit in attempting to drive the dome back up to voltage.

V. Beam Transport System

The requirement of dual beam operation imposes special constraints on tuning the injector beam lines.[5] Both beams must be properly matched to the linac both in longitudinal and transverse phase space. The transport lines have been designed so that the necessary tuning in both beams can be done before the beams are blended in the final common section of beam line. A schematic diagram of the transport line is shown in Fig. 1 and a photograph of the actual installation is shown in Fig. 5.

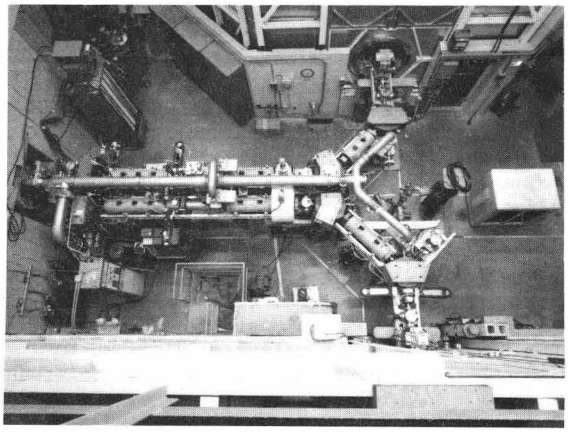

Fig. 5. Injector beam transport system.

In the longitudinal phase space, the beam energies must be the same so as not to induce longitudinal oscillation in the linac. Both beams pass through the main buncher, which is set to bunch the high current H^+ beam. Separate prebunchers are provided upstream in both beam lines so that some independent control on longitudinal phase space can be effected for each beam. The bunching is optimized for the H^+ beam and some overbunching will occur in the lower current H^- beam.

In the transverse phase space, the tuning is more complicated. The H^+ beam is again considered the primary beam and is tuned first to produce a waist in the buncher. Emittance scans are then taken at this point and the quadrupole gradients of the final two doublets are set to match this beam to the linac. Once this match is established, the required low current H^- beam that must be produced at this same emittance measuring station to give a simultaneous match for the H^- beam is calculated by running the H^- beam backwards in the transport calculation. Then, intermediate emittance measurements are made on the H^- beam and the matching from the intermediate emittance station to the final emittance station is carried out. The final doublets are left at the gradients previously determined for the H^+ beam. Some tuning of the quadrupoles upstream of the intermediate emittance station in the H^- beam transport line is usually required to achieve an overall match. The H^- beam in general does not have a waist in the final buncher, but the beam size is adequately small and emittance degradation in the final buncher is usually not as much a problem as in the prebunchers, where it is difficult to achieve small beam sizes.

Initially, it was planned to inject both beams into the linac on the linac axis. In practice, it has proven expedient to separate the two beams in the vertical plane to compensate for an offset further down the linac. Fixed apertures were installed in the final section of the beam transport line to constrain the two beams to the same axis and it has been necessary to enlarge these apertures temporarily to permit this separation and to permit high peak current tests to be conducted. The final choice of aperture size has not been established.

Production beams to date (100 μA average H^+ beam simultaneous with up to 10 μA H^- beam) have not required sufficiently high peak currents of H^+ beam to make the quadrupole gradients of the final doublets differ appreciably from the zero current case. Thus, the matching has not yet posed any real problem or compromise in running simultaneous beams. However, as the H^+ peak current is raised, the gradients of the final doublets will have to be significantly increased to match these higher peak currents to the linac and the tuning of the H^- beam will have to be adjusted for each value of H^+ peak current. The buncher amplitude will also be raised as the H^+ peak current is increased, but this change should have only a minor effect in longitudinal matching, since the first tank of the linac is designed to effect proper tailoring of the longitudinal emittance.

Theoretical solutions to achieve the dual match have been achieved for most anticipated beams using the beam envelope transport code TRACE. It is now known, however, that the results of the calculations are not in agreement with observed empirical matching gradients needed for fully bunched, high peak current beams. There is no disagreement for the low peak current beams. More detailed computer simulations are now being considered.

The common portion of the beam transport line has been made as short as possible so that there is no significant distortion of the transverse phase space distributions of the low current H^- beams by the high current H^+ beams. Thus, matching exercises can be done independently and then the beams superimposed. It is anticipated that as the H^+ beam current increases there will be increasing difficulty in achieving exact match for the H^- beam and that beam spill in the linac from the H^- beam may limit the amount of H^- beam that can be simultaneously accelerated. Experience to date indicates that the higher emittance H^- beam is harder to tune than the higher current, but lower emittance H^+ beam.

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DISCUSSION

J. McKeown, CRNL: What is the amplitude variation in current during the pulse width?

McConnell: Risetime of the pulse is 36 μs from 10-90%. The amplitude of the current is constant from the peak for the duration of the 500 μs pulse width.

McKeown: Have you operated at wider pulse widths than 400 μs at a reduced pulse repetition rate?

McConnell: We have not operated at pulse widths greater than 500 μs.