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Volume I

Compiled by R. A. Jameson and S. O. Schriber

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ACCELERATOR TECHNOLOGY PROGRAM

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ABSTRACT

This report presents highlights of the major projects in the Accelerator Technology (AT) Division of the Los Alamos National Laboratory. The first section details progress associated with the accelerator test stand. Following sections cover achievements in accelerator theory and simulation, LAMPF II accomplishments, and updates on BEAR, beam dynamics, the rf laboratory, p-bar gravity experiment, University of Illinois racetrack microtron, and NBS microtron. Also included are results from the Proton Storage Ring commissioning, developments in very high microwave systems, and advances in the Fusion Materials Irradiation Test rf technology. In addition, the Phoenix Project and the Krypton Fluoride Project are discussed. The report concludes with a listing of papers published by AT-Division personnel during this reporting period.

ACCELERATOR TEST STAND

INTRODUCTION

Significant progress has been made in several areas associated with the Los Alamos accelerator test stand (ATS) during this reporting period. The ion-source research program has continued to address key issues in the optimization and understanding of surface-plasma ion sources. Detailed spectroscopic studies have allowed determination of several of the source-plasma parameters. These measurements represent a first step toward the development of a theoretical model of the surface-plasma source physics. Experimental and theoretical studies of beam-transport neutralization have expanded our understanding of this important phenomenon. A new, noninterceptive, beam-neutralization diagnostic has been developed and is currently being tested. Anticipating the long-range requirements of the Neutral Particle Beam (NPB) program, the ion-source section has launched a volume-source research effort. Initial tests have begun, using an optimized cusp-field source.

Major advances have been made in the ATS diagnostic-development program. The laser-induced-neutralization diagnostic approach (LINDA) for determining the longitudinal emittance of the beam at the output of the ATS radio-frequency quadrupole (RFQ), has been successfully demonstrated. Near-term application of this unique diagnostic will be to measure transverse emittance in the ATS. An x-ray diagnostic has been successfully developed for the absolute measurement of the peak-vane voltage on the ATS RFQ. This technique has also been demonstrated and was recently utilized in vane-surface "Kilpatrick" studies. A noninterceptive beam current monitor has been developed and is now routinely used in the ATS buncher. Because of the very compact nature of the buncher, this current pickup is the only beam diagnostic between the RFQ and the drift-tube linac (DTL).

A new RFQ (RFQ III) was installed and tested on ATS. The design improvements incorporated into RFQ III have resulted in a system of high reliability with few high-voltage breakdowns. Researchers from the California Institute of Technology used the RFQ III output beam for gamma-ray generation studies.

Motivated by the demanding long-range requirements of an NPB rf-power system, we initiated an experimental investigation of rf-structure Q enhancement obtainable by cryogenic techniques. Initial measurements at liquid helium

temperatures on a single-cell pillbox-like rf cavity have demonstrated Q gains as high as 4.3.

The ATS DTL was successfully stabilized, tuned, and matched to the rf power supply by the Structures Development Laboratory in the Linac Technology Group (AT-1) of the Accelerator Technology (AT) Division. After the completion of exhaustive and extensive tuning procedures, an axial electric-field distribution “flat” to within $\pm 5\%$ was obtained. The mating of this rf structure to the ATS RFQ should allow the generation of a 5-MeV particle beam and, thus, attainment of a major milestone in the NPB program.

Beam sensing studies have been carried out using the Los Alamos Van de Graaff accelerator. This work has resulted in the experimental demonstration of beam-direction sensing to a precision of approximately 10 μ rad. Also studied on this facility was the neutralization of 1- and 2-MeV beams using a pulsed gas-jet neutralizer. Neutral fractions of about 50% were observed with an optimal pressure of xenon.

Ion Source

The Ion Source Section of the Neutral Beam Technology Group (AT-2) has concentrated its efforts on the following:

- Operation and maintenance of the 100-kV, 100-mA ATS injector
- Injector upgrades and improvements
- Development of the 4X scaled Penning source
- Optical-spectroscopic measurements of the source-plasma parameters in the 4X source and the small-angle source (SAS)
- Beam-transport-neutralization measurements and theory
- Initial tests of a cesium-free volume-type source

The 100-kV Injector

The 100-kV injector has been used for the past two years to supply H^- beam to the ATS RFQ. During this time a maximum current of 95 mA has been accelerated to 2 MeV. However, the current from the injector must be increased in order to reach and exceed the goal of 100 mA at the high-energy end of the RFQ. Higher currents from the source have been obtained by extracting the beam at higher than the

original 22-kV design voltage. We have modified the extractor regulator to allow pulsed operation in an attempt to achieve reliable extraction at 25 kV or higher. This modification has proved very successful, and we have reached nearly 200 mA on the ion-source test stand (ISTS) and have extracted about 160 mA on the injector at a somewhat lower extraction voltage. Although the beam emittance measured on the ISTS did not increase with the increased current and extraction voltage, substantial growth was observed for the 100-kV injector beam at the RFQ entrance. This growth was probably caused by accelerating-column aberrations. We are considering column aperture modifications or the positioning of quadrupole focusing magnets between the source and the column as means of preventing the emittance growth.

For the short (~ 100 μ s) RFQ pulses now used, it has not been necessary to regulate the accelerating-column voltage. However, we are now designing a regulator that can be used in future experiments where longer RFQ pulses are anticipated. An Eimac Y847 165-kV triode will be employed as a series-pass tube between a 100-kV power supply and the column. This configuration will allow column-voltage regulation, at about 75 kV, to $< 1\%$ for load-current pulses of 0.5 A, which would be adequate for a 250-mA beam. The regulator is designed to work with any power supply capable of supplying the required average current, with the pulse current being supplied by a capacitor. This voltage regulator system is being built in collaboration with the Medium Energy Physics (MP) Division, which has a requirement for a similar system.

Source Emission Aperture Studies

To investigate the origin of beam emittance in the SAS, we carried out a series of measurements using unshaped and shaped emission apertures. The aperture geometries are shown in Figs. 1(a) and (b), along with ion-optical calculations of particle trajectories obtained from the code SNOW assuming zero ion temperature. Figures 1(c) and (d) display graphs of the calculated emittance versus beam fraction, using the minimum ellipse algorithm.¹ The shaped-aperture design was supplied by John Whealton of Oak Ridge National Laboratory (ORNL). Experimentally, the emittances were observed to be essentially equal for these two geometries. An important result of these studies was the observation that the projection of the emittance data to the source showed a substantial spatial non-uniformity in the emission current density along the length of 7-mm slit. Such a nonuniformity would mask the effect of ion-optical aberrations downstream of the source.

target current — 13.223 A/m, accelerator current — 0.000 A/m,
 accelerator voltage — 22000.0 V, plasma current — 20.000 A/m

(a)

target current — 13.223 A/m, accelerator current — 0.000 A/m,
 accelerator voltage — 22000.0 V, plasma current — 20.000 A/m

(b)

Fig. 1. Shaped and unshaped emission apertures. (a) and (b): aperture geometries and particle trajectories. (c) and (d): calculated emittance vs beam fraction.

4rms and Minimum Emittance vs Beam Fraction

(c)

4rms and Minimum Emittance vs Beam Fraction

(d)

Fig. 1 (cont.). Shaped and unshaped emission apertures. (a) and (b): aperture geometries and particle trajectories. (c) and (d): calculated emittance vs beam fraction.

We are now investigating the origin of the nonuniformity with the aim of improving the total current available as well as achieving a reduced emittance and beam divergence.

Beam-Transport Neutralization

Space-charge neutralization of the beam by ionization of the background gas in the 20- and 100-kV beam transport region has been shown experimentally to be effective to within approximately 1%. This phenomenon is of significant importance in the understanding of beam-transport physics because of the existence of beam instabilities observed at low-background pressure in our injector. Instability-induced emittance growth by factors of 2-3 were eliminated by adding xenon background gas to the system. Theoretical studies² have shown that an ion-ion instability can be excited at very low background electron densities and that a negative beam potential would be consistent with the low-electron-density background. At sufficiently high background pressure, the beam potential is positive, trapping electrons, and the instability amplitude is saturated at a low level by heating the electrons. At high pressure, the instability does not affect the beam.

More recent theoretical studies³ of beam instabilities in the transport region have been carried out using a time-dependent PIC code. In these simulations the beam is injected into a transport region that contains a given neutralizing gas pressure, and the time evolution of the beam and gas parameters is calculated. The simulations indicate that at low background pressure the beam potential is predominantly negative, inhibiting electron trapping and enhancing ion-ion beam instability. Significant instability-induced emittance growth is predicted and a steady-state equilibrium is not obtained. As the gas pressure is increased, the beam potential oscillates positive and negative, allowing some electron trapping and instability damping. At high pressure, a positive beam potential is obtained within a few microseconds, trapping a sufficient electron population to damp rapidly the ion-ion instability. In this case a steady-state equilibrium is rapidly obtained and the emittance growth is low.

Measurements⁴ were made of the beam potential in the 4X source, using an emissive probe inserted into the beam at various radii. At sufficiently high background pressure, the observed beam potential was positive. At low pressure, the probe probably perturbed the beam too much to give reliable results; the indicated potential had oscillations and tended to be negative. In an attempt to make

nonperturbing beam-potential measurements, we have studied the ion optics of two noninterceptive techniques (Fig. 2). Both methods deduce beam potential by analyzing the energy of slow ions (or electrons) leaving the beam radially. The four-grid method was chosen because of its simplicity and because the large current of low-energy particles anticipated from our beam makes a Faraday-cup detection method possible. The energy is analyzed by varying the retarding potential of the decel grid. We expect resolution of better than 1 eV and a bandwidth of several megahertz. This device has been built, and tests are now being conducted on the ISTS on 20-kV beams.

Fig. 2. Four-grid, parallel-plate analyzers.

The 4X Source

To produce a beam having a round cross section, with symmetric emittance, and to achieve higher duty factor, we built the 4X source and the accompanying high-current test stand (HCTS). This source is scaled up in size and down in power density by a factor of 4 relative to the present injector source, the SAS. Although the extracted current has not yet exceeded 120 mA, the brightness of the 4X source has

exceeded that of the SAS, and the 4X has operated in a quiescent mode. The performance of this source is still being investigated. To diagnose the plasma, we have mounted a 1-m optical spectrometer (Fig. 3) to measure widths and intensities of the Balmer α , β , γ , and δ lines in H_2 and D_2 discharges. These measurements are used to deduce the plasma density and electron and atom temperatures in the source plasma; the atom and H^- temperatures are thought to be about equal. Determination of the plasma parameters is a first step toward developing a discharge model for the source. The experimental results⁵ show that the atom temperature increases with discharge current, attaining 1-2 eV at the highest current. We now have optical spectrometers on both the ISTS and HCTS and are continuing the studies. Some of the spectroscopically measured plasma parameters are given in Fig. 4 for different discharge modes (described in detail in Ref. 5). We have just completed installing the computer interface to the emittance scanner on the HCTS and have begun emittance measurements. We have operated the 4X source at about 5-mA dc and are preparing a cooled version to attempt to reach higher average current, both pulsed and dc.

Fig. 3. Optical-spectrometer experimental arrangement on the 4X source.

DERIVED PLASMA PARAMETERS

Source (Discharge mode)	Electron density (10^{14}cm^{-3})	Hydrogen atom energy(eV)	Electron Distribution Temperature			
			from Mo I (eV)	from Cs I (eV)	from Cs II (eV)	from H I (eV)
4X(I)	1.0	1.5	0.49	--	0.72	--
4X(II)	1.4	1.9	0.50	0.50	0.93	--
4X(III)	1.7	1.6	0.55	--	0.72	0.33
SAS	1.7	2.0	--	--	--	0.25

Fig. 4. Spectroscopically measured plasma parameters.

The Volume Source

We have participated in a collaboration on construction and testing of an optimized cusp-field volume source of H^- ions. This source was built by Ehlers and Leung⁶ of Lawrence Berkeley Laboratory (LBL), and initial beam tests were carried out by York and Stevens⁷ of Los Alamos on the LAMPF test stand. In these experiments, current densities of up to 38 mA/cm^2 were obtained, and the measured emittance indicated an ion temperature of less than 1 eV for the core of the beam. Detailed measurements were made to compare its performance to that of the original prototype⁷ and to determine the dependence of beam emittance on the operating parameters. Tests of this volume source were recently initiated in AT Division. The experiments are being continued on the ISTS, which has the high-arc current and high-voltage and gas-handling capabilities that are thought to be required to reach $>100\text{-mA}$ beam current. A high-perveance extraction system has been designed using the positive-ion code SNOW. If the plasma can be produced and the electron loading is modest, a current of 140 mA is predicted at an extraction voltage of 29 kV. We anticipate reaching $>30 \text{ mA}$ at previously used arc currents, and we can now go to twice the current and voltage previously used.⁷ This source mounted on the ISTS

is shown schematically in Fig. 5. Initial tests have begun, and a beam current of 8 mA has been measured. Several months of testing will be required to explore the range of operating parameters thought to lead to beam current and emittance of interest for our program.

Fig. 5. Volume source on the ion-source test stand.

LEBT

The low-energy beam-transport (LEBT) region was upgraded by installing linear position encoders on two of the most frequently moved permanent-magnet quadrupoles (PMQ) units. A new PMQ mounting setup has been designed for the LEBT and has been mocked up for tests. This setup will allow remote, continuous movement of as many as six PMQs to any position along the LEBT beamline and has linear position encoders on each PMQ. The present arrangement allows only a 1-in. travel for each PMQ.

RFQ

Beam was injected, transmitted, and accelerated in the ATS RFQ III on March 14, 1986. Even though the input beam was poorly matched in this initial test,

50 mA out of the 100 mA injected were accelerated. In anticipation of the California Institute of Technology (Cal Tech) experiments, discussed below, and the exploratory nature of the early experiments with RFQ III, the injected beam was reduced to 20 mA or less. RFQ III has proved to be reliable and has few high-voltage breakdowns; this behavior is attributed to the new vane-tip design and the resultant lower-peak fields. The "Q" of the RFQ has gradually improved with conditioning from a value of 5300 to 7300. The theoretical best value is 10 000.

Cal Tech Gamma-Ray Experiments

A high-energy-physics group from Cal Tech became the first user group on ATS. They used the beam from RFQ III to generate 17-MeV gamma rays from the interaction of protons on lithium. Cal Tech is studying the feasibility of using an RFQ to generate these gamma rays, which in turn will be used to calibrate a large calorimeter for a future CERN experiment.

RFQ Vane Voltage Measurements

A diagnostic has been developed that provides an absolute measurement of peak vane voltage on the ATS RFQ III. This diagnostic uses the characteristic x-ray emissions from the RFQ to make a noninterceptive measurement of the continuum of x-ray energies emitted. The peak x-ray energy in the spectrum should correspond to the peak voltage across adjoining vanes in the RFQ.

Because the x rays of interest are produced by electrons accelerated across the gap between adjoining vanes, the x-ray monitor is positioned to view a small region of the vane tips near the high-energy end of the RFQ. A port provides an unobstructed view of the high-voltage region of the vanes through a manifold-coupling slot and the open region of one of the RFQ quadrants. The bremsstrahlung x rays are monitored through the port by an NaI(Tl) photon detector with an energy resolution of approximately 10%. A spectrum of x rays is collected from the RFQ, and its energy end point is extrapolated, based on the calibration obtained from a radioactive gamma source. Although the x-ray diagnostic technique is not intended for routine day-to-day measurements, it provides a direct determination of the electric-field level within the RFQ that can be used to calibrate simpler diagnostic systems. The x-ray measurements remove inherent ambiguities associated with the estimation of

the vane voltage from rf power measurements. As an example of these ambiguities, Fig. 6 illustrates the difference, at a given vane voltage, between the RFQ power input determined from the directional coupler and that determined from the RFQ pickup loop. Because the pickup loop responds to the field level within the vane structure, this diagnostic is directly sensitive to the vane voltage. Accordingly, a measurement of the vane voltage can be routinely obtained on a day-to-day basis once the pickup loop is calibrated against the x-ray measurements. This calibration process is currently being carried out.

Fig. 6. RFQ power input determined from the directional coupler and the RFQ pickup-loop diagnostics.

RFQ Vane-Surface Kilpatrick Studies

The AT-2 Radio-Frequency Structures Section has initiated a series of "Kilpatrick" experiments to investigate the performance of an rf structure operated

with intense electric-field gradients. The ultimate objectives of these experiments are the following:

- Evaluate component surfaces for suitability in an rf structure
- Understand the high-voltage-breakdown mechanisms
- Increase the capacity of an rf structure to sustain intense electric fields without breakdown

The Kilpatrick criterion is used as a basis for comparing results of these experiments with those of other applicable studies and the performance of related rf structures. This criterion is an electric-field-level specification below which high-voltage breakdown (sparking) would not be expected to occur; above this level, sparking may occur. The Kilpatrick criterion applies to both dc and rf fields and provides a means of comparing electric-field limits at different rf frequencies.

The rf structure used in the present experiments is an RFQ operated near 425 MHz, the present operating frequency of the ATS RFQ. The structure vanes are 6 in. long and are similar in design to those of the ATS RFQ in the region of the vane tips (the region of high-electric-field gradients). By using this short RFQ structure, sufficient power is available to drive the structure to the breakdown point. The vanes are interchangeable so that effects of different vane surfaces can be investigated. In the studies discussed below, two different sets of vanes have been evaluated. Both vane sets were bright-acid copper-plated steel vanes. One set was electropolished in the Materials Science & Technology Division at Los Alamos; the other set was tested without electropolishing. In these experiments, the RFQ electric-field levels were determined by measuring the x-ray emission (this diagnostic technique is discussed in the section on RFQ vane-voltage measurements). The x-ray measurements were complemented by data from several other diagnostics such as power-level monitors, vacuum recorders, and videotape monitors of visible radiation. In addition, detailed studies of the vane-surface microstructure have been carried out. The x-ray measurements were taken after conditioning of the RFQ.

For the nonelectropolished vanes, the rf conditioning time was approximately 50 hours; once conditioned, the RFQ could be reconditioned in about 1-1/2 hours after being exposed to atmospheric pressure. Figure 7 shows the x-ray data as a function of photon energy for an rf pulse width of 100 μ s. In Fig. 8 the same data are plotted against the Kilpatrick criterion. The relatively high Kilpatrick value of about 4 decreases somewhat as the rf pulse length is increased, as illustrated in Fig. 9,

Fig. 7. X-ray counts as a function of x-ray energy for an rf pulse width of 100 μ s. Nonelectropolished RFQ vanes.

Fig. 8. X-ray counts as a function of the Kilpatrick value for an rf pulse width of 100 μ s. Nonelectropolished RFQ vanes.

Fig. 9. X-ray counts as a function of the Kilpatrick value for an rf pulse width of 1000 μ s. Nonelectropolished RFQ vanes.

which shows the Kilpatrick value from the x-ray emission obtained with an rf pulse width of 1000 μ s. It should be noted that the surface of the vanes in the ATS RFQ was generated by the same process as that used for the vanes in these experiments.

With the electropolished vanes, the RFQ could only operate at significantly reduced electric fields, about 2 Kilpatrick. After electropolishing, the vanes showed evidence of chemical spotting. Detailed examination of the surface microstructure revealed areas of surface etching and pitting, with the corresponding opening of grain boundaries. The degradation of the Kilpatrick value observed with these vanes can apparently be attributed to the surface imperfections resulting from the electropolishing process.

ATS/RFQ Longitudinal Emittance Measurement Using the Laser-Induced Neutralization Technique

With increasing brightness, beam diagnostic techniques requiring interception of the beam become impractical. For H^- particle beams, solutions for this problem

based on the phenomenon of photodissociation are currently under investigation on ATS. A laser is used to neutralize selectively portions of the beam that can be characterized after the charged particles have been swept away. The beam parameters at the point of neutralization are then simply reconstructed by using only the drift distance for the neutralized portion of the particle beam. In principle, this technique can be used to reconstruct the complete 6-D phase-space density distribution by altering the spatial and/or temporal structure of the photon field traversing the particle beam and using the appropriate detector geometry.

We have used LINDA to measure the longitudinal parameters at the exit of the 2-MeV ATS RFQ. Before these measurements, we used LINDA to determine the current density versus longitudinal-phase and longitudinal-energy distribution of the beam in ATS; these results have been reported.⁸ Figure 10 indicates the experimental layout and beam configurations for our measurements. A single transverse

Fig. 10. Experimental arrangement and beam configurations for longitudinal-emittance measurement using the laser-induced neutralization diagnostic approach.

slice of the microstructure is neutralized with a 1.06-mm Nd:YAG mode-locked laser capable of output energies of up to 10 mJ for a single 32-ps pulse. A telescope and a cylindrical lens are used to expand the laser beam to 7 mm in the transverse dimension and to a focus of less than 30 μm in the longitudinal dimension at the point of intersection with the 3-mm particle beam, 5.7 cm from the exit of the RFQ. The neutralization fraction for the portion of H^- beam illuminated by the laser is estimated to be 0.99 (well into saturation) for the 1- to 3-mJ pulse used. At this power level, 10% variations in laser power has negligible effect, and reflections below the 1% level can be ignored.

The time at which the laser fires can be controlled only to within a few microseconds; therefore, the 413-MHz RFQ phase is random with respect to the time when the laser pulse traverses the particle beam. The relative phase for the sampling portion of the beam is determined by a computer-interfaced interval timer having approximately 15-ps resolution. An InP:Fe photodetector, having a rise time of less than 100 ps, is positioned in the laser beam downstream from the interaction point and is used to provide the start for the interval timer. The negative-going zero-crossing point of the vane potential as measured near the exit of the RFQ tank is used for the interval-timer stop point. System temporal resolution is estimated to be approximately 30 ps. To ensure laser, ion-source, and RFQ stability during data acquisition, additional electronic components are included to veto events for which the laser power, source current, or RFQ power fall below a predetermined discrimination level.

For longitudinal emittance measurements, the neutral-particle detection system consists of a subnanosecond secondary-emission monitor (SEM) with an active area of 4.1 cm^2 , a 450-MHz, 105X amplifier, and a waveform digitizer interfaced to a computer with IEEE Standard 488 interface. A second InP:Fe photodetector in the laser beam initiates data acquisition so that time-of-flight information can be taken from the digitized SEM waveform. A temporal dispersion in the 32-ps sample of the particle beam is produced by a 7.57-m drift between the point of neutralization and the SEM. Although this drift distance obviates the use of multigigahertz detection apparatus, less than 5% of the neutralized portion of the particle beam is collected.

The relative-phase and energy profiles of the H^- particle beam are extracted from the interval timer values and the digitized waveforms. To build up an emittance profile over many macropulses, each waveform is binned in terms of phase and energy and averaged with any previous samples. The raw emittance plots must

be corrected to remove the 413-MHz rf background and the aberrations of the waveform digitizer. Additionally, secondary laser pulses (occurring at 7-ns intervals after the primary) produce artifacts in the data that must be removed. Because the tails of these distributions overlap at 1-5% of the peak values, the software cuts used to remove these artifacts are somewhat arbitrary at these levels.

Figures 11 and 12 show contour plots of the longitudinal-emittance profile after background subtraction and software cuts have been implemented. Figure 11 is an

Fig. 11. Contour plot of longitudinal emittance profile after background subtraction and software cuts have been implemented. Vane voltage assumed to be near design value (410 mV at rf pickup loop).

emittance plot for an 82-mA, 2-MeV beam that was injected into the RFQ at 93.5 keV and was accelerated at an RFQ vane voltage assumed to be near the design value (410 mV at the power-sensitive rf pickup loop). Figure 12 is the result of a subsequent run with the same conditions except that the RFQ vane voltage was reduced (380 mV at the rf pickup loop) to a point above threshold for 2-MeV

Fig. 12. Contour plot of longitudinal emittance profile after background subtraction and software cuts have been implemented. Vane voltage (380 mV at rf pickup lo p) below assumed design value.

acceleration but below the design value. Figures 13 and 14 are projections of the emittance data on to the energy and phase axes.

The Accelerator Theory & Simulation Group (AT-6) has calculated the transverse and longitudinal phase-space parameters versus vane voltage. Two predictions using the particle-dynamics code PARMTEQ are shown, Figs. 15(a) and (b), for the longitudinal phase-space distribution at the output of the ATS RFQ. The input-particle distributions were constructed to be consistent with the transverse emittance-scanner measurements immediately before the longitudinal laser measurements. The input energy, beam current, and RFQ operating frequency were taken to be the same as those during data acquisition. Figure 15(a) displays the results of the PARMTEQ calculations for the RFQ vane voltage at the design value

Fig. 13. Projection of emittance data onto energy and phase axes. Vane voltage assumed to be near design value (410 mV at rf pickup loop).

Fig. 14. Projection of emittance data onto energy and phase axes. Vane voltage (330 mV at rf pickup loop) below assumed design value.

Fig. 15. PARMTEQ prediction of longitudinal phase-space distribution at output of ATS RFQ: (a) RFQ vane voltage at design value $V/V_0 = 1$, (b) RFQ vane voltage below design value, $V/V_0 = 0.85$.

$V/V_0 = 1$, and Fig. 15(b) shows the results, assuming a vane voltage $V/V_0 = 0.85$, well below the design value. The output from PARMTEQ was analyzed with the same moments-analysis code used to analyze the data. The measured FWHM energy distribution of 1.25% for the 140-mV data is consistent with the prediction for $V/V_0 = 1$, but the observed tail in the distribution suggests that at least some component of the data is at a lower vane voltage. The measured FWHM phase distribution of 50° is inconsistent with PARMTEQ predictions for any value of V/V_0 .

Although a matter of some debate, PARMTEQ predicts substantial cyclic variations in the average phase angle with respect to the vane voltage for an RFQ not operating at the design frequency. These cyclic variations are not predicted for an RFQ at the design frequency. For the 2-MeV ATS RFQ at the time of the longitudinal measurements, PARMTEQ predicted $\pm 20^\circ$ in phase angle and a periodicity of 10% in V/V_0 for vane voltages near $V/V_0 = 1$. Figure 16 shows a PARMTEQ prediction, assuming a Gaussian distribution in vane voltage centered at $V/V_0 = 0.925$ with a total spread of only 5%. The effect is to broaden the distribution in phase but to affect the energy distribution minimally. Because the RFQ amplitude-control feedback loop was not closed during the longitudinal measurements and the data acquisition time was inordinately long, a variation in vane voltage sufficient to produce the measured phase distribution is plausible. As is to be expected, below design vane voltage (Fig. 15), the tails of both energy and phase distributions increase as more particles fall from the bucket distorting the ellipse

parameters. However, little significance can be attached to these tails if the longitudinal phase space is the result of time averaging over too large a variation in vane voltage. Detailed comparison of measured ellipse parameters with those predicted will be made for the ATS RFQ III, which will be operated at the design frequency and with the amplitude feedback loop closed.

Fig. 16. Longitudinal phase-space plot predicted by PARMTEQ, assuming a Gaussian distribution in vane voltage centered at $V/V_0 = 0.925$.

Power-Flow Droop and Power-Flow Phase Shift

The power-flow droop and phase shift in an RFQ have been estimated analytically by adding loss terms to the simple two-port transmission-line model. For an RFQ driven at one end and terminated at the other end by an open circuit, the results of this analysis yields the power-flow droop given by

$$\frac{\Delta V}{V} = 0.5 \frac{\omega^2}{c^2} \frac{L^2}{Q},$$

and the corresponding power-flow phase shift of

$$\Delta\phi = 0.5 \frac{\omega^2}{c^2} \frac{L^2}{Q} .$$

Here, V is the voltage at the open end, ω is the rf angular frequency, L is the RFQ's length, and Q is the system Q . If the RFQ is driven in the middle, $\Delta V/V$ and $\Delta\phi$ are reduced by a factor of 4.

The power-flow phase shift and power-flow droop are negligible for RFQs of current dimensions. At higher frequencies, the power-flow phase shift and droop could become important for long RFQs. However, long RFQs are not practical without some form of longitudinal stabilization that, itself, would eliminate the power-flow phase shift and reduce the power-flow droop. Therefore, it is reasonable to conclude that power-flow droop is not a problem in RFQs, except perhaps in the case of a long RFQ with very heavy beam loading. At beam currents greater than 1 A at beam energies of 2 MeV or more, the power-flow phase shift and droop might begin to be a concern.

BUNCHER

Beam Current Diagnostic

A noninterceptive beam current monitor has been built and installed in the ATS buncher. This beam diagnostic is a capacitive-type pickup system including two 1.6-cm-long coaxial cylinders that surround the beam path. This pickup approximates a 50- Ω strip line that is connected to a 50- Ω low-dispersion coaxial cable. Because of the short length of the pickup and the attenuation of higher harmonics of the signal that is due to the low velocity of the beam particles, the raw signal from the pickup appears as a distorted 425-MHz sine wave. This raw signal is rectified with a calibrated rf-crystal detector. The system was calibrated over a range of beam currents by comparing the signal amplitude from the crystal detector with beam current measured with a wide-band pulsed-current transformer. As expected, the measured crystal detector's output signal is dependent on the square of the beam current. Because of the very compact nature of the buncher, this current pickup is the only beam diagnostic between the RFQ and the DTL.

DRIFT-TUBE LINAC

DTL Spill-Power Dependence on Buncher Phase

The phase of the rf power on the buncher is adjustable. There was some concern that operation of the ATS buncher with incorrect phase during startup could result in the beam striking the wall some place within the DTL and thus produce a "hot spot." This situation was simulated by AT-6, using the codes PARMTEQ and PARMILA. The input particle distribution to the buncher was obtained by making a PARMTEQ run for the RFQ. PARMILA was used to follow the beam through the buncher, matching section, and DTL. Figure 17 shows the beam spill as a function of the buncher phase. The plot is for a 100% duty factor and 100-mA beam current. During turn-on in the ATS experiment, the duty factor was less than 0.1%. Accordingly, the very low values of spill power observed in the calculations indicate that hot spots should not be expected in the experiment.

Fig. 17. Maximum spill power occurring in a single DTL cell versus buncher phase for 100% duty factor and 100-mA beam.

DTL Cryogenic Cavity Studies

In projected space demonstrations of the NPB concept, the total weight of the rf-power systems is obviously a critical issue. The successful demonstration of accelerator-cavity operation at cryogenic temperatures would have significant impact on the system's power requirements. In anticipation of long-term requirements for the NPB program, the AT-2 Radio-Frequency Structures Section has launched an experimental investigation of the performance enhancement obtainable with cryogenically operated rf structures. The immediate objectives of the present small-scale experiments are to accomplish the following:

- Measure the Q enhancement of a one-cell DTL structure at cryogenic temperatures
- Investigate cryogenic Q enhancement as a function of rf-power level

Initial experiments were carried out on a one-cell DTL structure immersed in liquid nitrogen. Figure 18 is a schematic of the experimental apparatus and illustrates the characteristic system dimensions; Q measurement is the primary experimental diagnostic. At low power, reliable Q measurements were obtained by reflection- and transmission-mode methods, both techniques agreeing to within

Fig. 18. Experimental apparatus used in cryogenic DTL cavity studies.

around 2%. At high power, successful Q measurements were made using the phase-shift method. The accuracy of the high-power data is estimated to be about $\pm 10\%$. The results of the initial experiments with LN_2 indicate a Q gain enhancement of 2.3 at liquid nitrogen temperature. This Q enhancement is essentially constant over an input power range of 1 mW to 65 kW. The rf structure became very stable at the LN_2 temperature. Little frequency shift (~ 7 kHz out of 450 MHz) was observed over the 2-day experiment duration, with the frequency remaining predominantly within 1 kHz of the original resonance. This frequency stability made it possible to jump rapidly to full power with only a slight frequency adjustment (~ 1 kHz).

In a subsequent experiment, an attempt was made to measure the Q gain at liquid helium temperature. Unfortunately, this experiment was conducted in a readily available liquid nitrogen Dewar, not a liquid helium Dewar. As a result, the DTL cavity was cooled by helium gas, and a thermal equilibrium was not obtained between the interior and exterior of the cavity. In spite of these difficulties, a Q enhancement of 3.3 was measured.

At liquid helium temperatures, a Q enhancement of 6 or more would be anticipated. Considering the best experimentally measured value of 3.3, it was hypothesized that some resistive element (such as an rf seal), whose Q is not temperature dependent, was distorting the experimental results. To test this hypothesis, a liquid helium experiment was carried out using a small pillbox-like rf cavity with brazed rf seals. In this experiment, a liquid helium Dewar was used, thus eliminating ambiguities associated with temperature gradients and the lack of thermal equilibrium. Initial Q -enhancement measurements with this experimental arrangement have demonstrated Q gains as high as 4.3.

Stem Power and Q Measurements on a DTL

In November 1985, S. A. Hassemer and J. H. Billen of AT-1 traveled to Chalk River Nuclear Laboratory, Ontario, Canada, for one week to make measurements on a 22-cell aluminum low-power DTL structure. This 375-MHz structure was equipped with insulated drift-tube stems and insulated post couplers, thus permitting measurements of the net rf power flowing on the stems and post couplers. The purpose of the measurements was to determine the effect of a ramped field distribution on the stem power and on the post-coupler power. The results of these measurements showed that the post couplers carry almost all of any unbalanced longitudinal currents that arise from ramping the on-axis electric field. The field is

ramped by rotating asymmetric tabs on the ends of the post couplers, effectively shifting the electrical center away from the geometric center of a drift tube. Currents flowing on the post couplers can be at least as high as the unperturbed wall currents in a DTL. Field ramps as high as 3.4%/cell were achieved on the 22-cell DTL. Higher field ramps as high as 8%/cell were achieved using longer asymmetric tabs on the post couplers in the 550-MHz, 40-cell DTL in the AT-1 Structures Development Laboratory.

Tuning the ATS Drift-Tube Linac

The 425-MHz DTL for ATS was delivered to the AT-1 Structures Development Laboratory on January 2, 1986, for field stabilization, tuning, and matching to the rf power supply. The DTL is equipped with 39 drift tubes and 2 half-drift tubes on the end walls, making it a 40-gap structure. Two aluminum end walls with movable half-drift tubes permit perturbation of the first and last cells' frequencies for measuring the tilt sensitivity. After tuning is completed, the aluminum end walls are replaced with copper-plated-steel end walls equipped with fixed-length half-drift tubes.

To achieve the desired frequency, the DTL has two copper bars running the length of the tank on either side of the drift-tube stems. Machining material off the tops of these bars increases the cavity inductance and lowers the resonant frequency. Two movable slug tuners dynamically tune the DTL, so the bars must be cut to a height that brings the structure's frequency within the range of the slug tuners. Power is driven through a waveguide coupling iris. An assembly containing the iris and a ceramic window for the vacuum seal bolts onto the middle of the DTL tank.

The complete tuning process for the DTL consists of four tasks:

1. Tuning the structure of 425.000 MHz for a given setting of the slug tuners.
2. Achieving at this frequency the desired on-axis electric field distribution.
3. Stabilizing this field distribution against tuning errors.
4. Matching the DTL structure to the rf power supply.

These four tasks each require modification of some mechanical component of the structure to achieve the desired result. The tasks, goals, tuning mechanism, and measurement techniques are summarized in Table I. Although the table lists only one tuning mechanism for each of the four tasks, the situation is not quite that simple. All of the adjustments interact with one another to some extent, so the tuning procedure is necessarily an iterative process. For example, if the post

TABLE I
DTL TUNING SUMMARY

<u>Task No.</u>	<u>Parameter Adjusted</u>	<u>Goal</u>	<u>Tuning Mechanism</u>	<u>Measurement Techniques</u>
1	Resonant frequency	425.000 MHz	Cutting of longitudinal copper bars	Look for maximum power transmitted from drive to pickup probe versus frequency
2	Field dist.	Constant E_0 in all cells	Rotation of asymmetric tabs on post couplers	On-axis bead pull while phase locked on resonance
3	Tilt sensitivity	Minimum field difference per unit tuning error	Lengthening or shortening of post couplers	Compare two bead pulls having opposite frequency perturbations to the DTL end cells
4	Matching to waveguide	VSWR = 1.3 overcoupled at final Q with 50% beam loading	Cutting of coupling slot	Measure forward and reflected power at the drive slot and loaded Q of cavity

couplers are slightly detuned, affecting mainly the tilt sensitivity, measurements show that both the frequency and the field distribution may also change. Indeed, if the field distribution changes near the coupling slot, then the coupling to the waveguide is also affected.

Most of the interaction among tasks can be minimized by first performing task 3 (stabilization) before attempting other adjustments. It is also advantageous to tune the post couplers with the DTL operating as close to 425.000 MHz as possible so that the post couplers do not become badly detuned when the copper tuning bars are finally cut to achieve the desired resonant frequency. The easiest way to do this tuning is to use slightly undersized tuning bars (lowering the DTL frequency) and to maintain the structure frequency at 425 MHz by adjusting the slug tuners. We were able to use this method because the original tuning bars proved to be too small. Before the final cut on the tuning bars, we added a cap of additional material. The tilt sensitivity after tuning the post couplers was about 2%/MHz from cell to cell. That is, if a 1-MHz frequency error were introduced (say, by detuning the end cells),

the post couplers hold the field in each cell to within 2% of its unperturbed value. This is about 100 times better than the tilt sensitivity without post couplers.

After the field distribution was stabilized against tuning errors, we proceeded with task 2, adjustment of the field distribution. The desired distribution is a constant average on-axis electric field E_0 defined for each cell by

$$E_0 = \frac{1}{L} \int_0^L E_z dz ,$$

where E_z is the on-axis longitudinal component of electric field and L is the length of the cell. Our bead-pull measurements do not measure E_0 directly. Instead, we extract the value of E_0 by normalizing the measured peak electric field E_p in a given cell to the ratio E_p/E_0 supplied by the program SUPERFISH. Symmetrically placed post couplers (for example, with tabs pointing straight up) tend to equalize E_p in adjacent cells of the DTL. The theoretical distribution of E_p/E_0 increases by $\sim 27\%$ from the low-energy (LE) to the high-energy (HE) end. Therefore, the E_0 distribution for symmetrically placed post couplers has an $\sim 27\%$ negative tilt from LE to HE end. By rotating post-coupler tabs toward the LE end and making local adjustments near the slug tuners and later near the coupling slot, we achieved the "flat" E_0 distribution shown in Fig. 19. Most of the cells are within $\pm 0.5\%$ of the average field. The shorter cells on the LE end are more sensitive to misalignments than are longer cells, making errors larger on the LE end. The very first cell is probably too high in

Fig. 19. Deviation of E_0 along length of the ATS DTL. Relatively flat distribution obtained by proper rotation of post-coupler tabs.

frequency by about 7 MHz because of the discontinuity in the space around the drift-tube stems near the end wall. Task 4 (matching the structure to the waveguide) proved to be the most difficult of all. The measurements involved measuring the forward and reverse power at a directional coupler in the drive transmission line to calculate the voltage standing wave ratio (VSWR). Another measurement determines the cavity Q . It was then necessary to scale these quantities to the final Q of the DTL operating with a 50% beam-loading factor.

A poor coax-to-waveguide transition in the drive line made the VSWR measurement and the Q more uncertain as we enlarged the slot for higher coupling. After we calibrated a waveguide directional coupler and installed it between the transition and the coupling slot, we were able to make reproducible measurements. However, because of the unavailability of the copper end walls of the DTL, we were forced to make the measurements with the aluminum end walls originally intended only for tilt sensitivity measurements. Without the copper end walls, the final unloaded Q of the cavity is uncertain by $\sim 20\%$. A slot size of $4.75\text{ cm} \times 15.55\text{ cm}$ results in a coupling factor at 50% beam loading of 1.80 (that is $\text{VSWR} = 1.8$, overcoupled) if the unloaded cavity Q is 30 000. If the cavity Q is 24 000, the over-coupling factor drops to 1.44. After we measure the actual unloaded Q , it may be necessary to mask a portion of the coupling slot with added material.

LOW-ENERGY BEAM SENSING

Beam-sensing and beam-neutralization studies have been carried out by members of AT-2 using the Ion Beam Facility (IBF) of the Los Alamos Van de Graaff accelerator. These efforts have focused on the following:

1. Data analysis of beam-direction-sensing, proof-of-principle experiments using the laser-resonance-fluorescence (LRF) technique.
2. Measurements of atomic excited-state distributions after collisional neutralization.
3. Test of a gas neutralizer prototype for the Beam Experiments Aboard Rockets (BEAR) experiment.

Topic 1 covers the only method of precisely determining the propagation direction of a neutral beam that has been examined experimentally. The measurements discussed in topic 2 are the first in a series to be performed during FY 86 for the purpose

of detailed comparison to the LRF results predicted by existing computer codes (BEAM and CASCADE). The success of the neutralization-prototype tests described in topic 3 illustrates the value of a facility like the IBF in providing a flexible and readily available source of particles for verification of concepts and/or development of subcomponents related to the NPB program.

Analysis of LRF Proof-of-Principle Data

During May and June of 1985, LRF proof-of-principle experiments⁹ were performed using 1- to 4-MeV particle beams of hydrogen and deuterium at the vertical Van de Graaff accelerator. The LRF method employs a Doppler-tuned laser beam crossing the particle beam to resonantly excite a strongly fluorescent atomic level of the beam particle. The narrow line width of the excitation atomic transition and the similarly narrow line width available from laser sources allow the appropriate angle for maximum excitation of the fluorescence level to be very precisely determined. If the laser direction is well determined (i.e., boresighted), then the maximum fluorescence angle provides the needed direction information for pointing an NPB device. (For a detailed explanation of the LRF concept see Ref. 10.)

Figure 20 shows three representative resonance curves from the May/June runs, indicating the progress to date in demonstrating high-precision beam-direction sensing. Figure 20(a) represents data taken during the May run, the first LRF resonance observed for a particle beam in the million-electron-volt energy regime. An improved laser apparatus was used to achieve the reduced resonance width of Fig. 20(b) for the same particle beam conditions as Fig. 20(a), namely, a 2-MeV deuterium beam with 50- μ rad divergence. The additional width reduction observed for a higher-velocity 2-MeV hydrogen beam is shown in Fig. 20(c). Further analysis of the data has shown that the centroid of such curves, and hence the mean beam direction, can be determined by fits with standard functions (Gaussian, Lorentzian) to better than 0.1 standard deviations. The observed width of 105 μ rad for Fig. 21(c) thus implies that beam-direction sensing has been experimentally demonstrated to a precision of ~ 10 μ rad.

Another area of interest concerning application of LRF to high-energy beams is the question of expected background rates caused by residual fluorescence of atoms excited in the neutralization process. As the particle beam's velocity increases, this residual fluorescence persists further downstream, requiring either an undesirable extension of the overall length of a space platform or the capability to observe the

RUN 154a: 2 MeV DEUTERIUM

Fig. 20. Observed LRF widths: (a) 2-MeV D⁰ (May data run), The (b) 2-MeV D⁰ (June data run, with improved laser apparatus), (c) 2-MeV H⁰ (June data run) angle between the laser beam and the particle beam is given relative to the appropriate angle for maximum excitation.

(b)

Fig. 20 (cont). Observed LRF widths: (a) 2-MeV D^0 (May data run), The (b) 2-MeV D^0 (June data run, with improved laser apparatus), (c) 2-MeV H^0 (June data run) angle between the laser beam and the particle beam is given relative to the appropriate angle for maximum excitation.

RUN 230: 2 MeV HYDROGEN

Fig. 20 (cont). Observed LRF widths: (a) 2-MeV D⁰ (May data run), The (b) 2-MeV D⁰ (June data run, with improved laser apparatus), (c) 2-MeV H⁰ (June data run) angle between the laser beam and the particle beam is given relative to the appropriate angle for maximum excitation.

LRF signal on top of an increased background level. The present progress in determining the trend of the LRF peak-to-background ratio with particle velocity is shown in Fig. 21. From the many scans analyzed, four were selected that were taken under similar conditions (except for the particle-beam velocity), and the ratio of the peak height to the background level at the peak position was plotted, on a log-log scale, as a function of the beam velocity. Comparison of the trend line to that predicted by computer simulations yields good agreement of the slope, although the observed signal-to-background level is smaller than predicted because the simulation code does not include sources of background other than residual fluorescence.

Fig. 21. Fluorescence peak-to-background ratio vs β .

Excited-State Populations After Neutralization

The subject of LRF backgrounds was further explored during an experimental run in March 1986. A pair of VUV spectrometers was mounted on the Van de Graaff beamline to examine the H° excited-state populations at several points downstream of the neutralizer. Using a combination of various beam velocities and spectrometer port positions, we were able to measure the Lyman α , β , γ rates at 18, 25, 36, 54, 75, 90, and 108 ns from the center of the neutralizer. Measurements were made with and without applied quenching fields (transverse electric fields) below the spectrometers for both optimal and greater-than-optimal gas pressures in the neutralizer. The quenching fields enhance the decay rate of the excited states. Examples of "quenched" and "unquenched" spectra are shown in Figs. 22 and 23, respectively.

Fig. 22. Quenched fluorescence spectrum for 2-MeV H, 0.5-m downstream of neutralizer cell.

Fig. 23. Unquenched fluorescence spectrum for 2-MeV H, 0.5-m downstream of neutralizer cell.

The unquenched spectra are primarily indicative of the instantaneous p-state and d-state level populations. The quenched spectra include large contributions from the s-state populations. Very preliminary comparisons of the unquenched spectra to CASCADE predictions are in reasonable agreement. When fully analyzed, the data taken with nonoptimal gas pressures will address the question of neutralizer performance with thicker-than-optimal foils.

Fast-Cell Neutralizer for BEAR

In October 1985, an experiment to determine the utility of a fast-cell (pulsed gas jet) neutralizer design to meet BEAR specifications was undertaken at the Van de Graaff. The neutralizer consisted of a simple tube assembly approximately 60 cm long of 2.54 cm i.d., with a gas supply connected through a Lasertechnics molecular beam valve mounted at the center of the tube. The stripper gas was introduced as a flow perpendicular to the bore of the cell and on a time scale short enough to ensure that the gas is contained in the cell during the beam pulse.

Particle beams of 1 and 2 MeV were passed through the cell with Faraday cups at the end of the beamline monitoring the three transmitted charge states H^- , H^0 , and H^+ . Neutral fractions of slightly over 50% were observed with an optimal pressure of xenon. The valve usually throws gas amounts within $\pm 7\%$ of the average value (for a given control setting). The extreme variations of up to $\pm 15\%$ do not significantly affect the neutral fraction transmitted if centered about the optimal value. As a result of these tests, the concept of a pulsed-gas neutralizer has been adopted as viable for the BEAR experiment.

BEAM-ENERGY SPECTROMETER

In anticipation of the upcoming ATS operations at 5 MeV, the beam-energy spectrometer was recalibrated for the higher energy beam, using the wire orbit technique. Measurements were made around equivalent beam energies of 2 and 5 MeV because magnetic saturation in the bending magnet caused the effective length to change between 2 MeV, the RFQ output energy, and 5 MeV, the DTL output energy. The magnet is well into saturation at 5 MeV as demonstrated by the fact that the required magnet current for these two energies is 26 and 83 A, respectively. The previous calibration used a xenon beam with the equivalent momentum of a 2.0-MeV H^- ion. The effect of fringe fields, changing effective lengths, and errors in bend angles are all included in both of these calibration methods. For 2-MeV operation, the two calibration methods gave measured energy values that differed by only 0.4%.

BENDING MAGNET FOR TRANSVERSE EMITTANCE MEASUREMENTS ON THE ATS

Determining the longitudinal emittance of the beam in ATS has been successfully demonstrated using LINDA. The next applications of this diagnostic technique will be to measure the transverse emittance in ATS. Because of the highly divergent nature of the beam as it exits the RFQ, the laser-neutralized beam can only drift about 17 in. to the particle detector; otherwise this beam will be collimated by the beam pipe and will be too large for the detector. In this short distance, the unneutralized (charge) beam must be separated from the desired neutralized beam. To effect this separation, a bending magnet made of rare-earth-cobalt (REC) material was designed, built, and tested. Space consideration dictated that only a REC magnet could meet the requirements of the experiment. The magnet design was based on simulation studies using the PANDIRA and TRACE codes. The field integral was measured to be 64.5 kG/cm, which is only 2.6% below the predicted value. The field measurement also showed that the magnet would perturb the beam emittance before the laser neutralization point. A magnet shield was constructed and was shown to negate this effect with only a minor acceptable change in the removal of the charged beam.

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ACCELERATOR THEORY AND SIMULATION

MAGNETIC OPTICS

The challenge of designing a magnetic optics system that will focus and direct a charged particle beam, while maintaining extremely small beam divergences, is a difficult one. In December 1985, a workshop was held to define the state of the art and to make suggestions for the development of a new magnetic optics code containing the best features of existing codes. The main motivation for such a new code is the NPB program, but such a code would have wide applications in the accelerator community. The present approach is to attack some of the NPB optics design problems in order to explore the limitations of some of the present codes. There are five main thrusts to the present program:

- A survey of the capabilities and shortcomings of existing codes with the objective of specifying parameters for a new code that would extend or complement what exists.
- Design of a beam expansion telescope of medium aperture and low aberration.
- Design of a 180° achromatic bending system that includes the effects of space charge.
- Development of new numerical integrators that can be used in the existing or proposed magnetic optics codes.
- Development of subroutines to describe the external forces, including options for analytically or numerically determined magnetic fields.

Survey of Existing Codes

The externally developed codes BEAM-TRACE, GIOS, MAD, MARYLIE, RAY-TRACE, TRANSOPTR, and TRANSPORT [both the Lawrence Berkeley Laboratory (LBL) version with space-charge and the Fermi National Accelerator Laboratory (FNAL) version with third-order aberrations] are now available in-house and, where appropriate, are being used on NPB problems. In addition, the internally developed codes PATH, TRACE-3D, and MOTER are being heavily used. This "trial-by-fire" is revealing the merits of the various codes and giving valuable intercomparisons.

Beam Expansion Telescope

The high-order codes GIOS MARYLIE, MOTER, and RAY-TRACE are being used to study the output telescope optics, where the effects of higher-order aberrations dominate. The challenge is to take a beam diverging essentially from a point source and produce a beam of fixed diameter and no divergence. The basic lens system is a quadrupole triplet. MARYLIE has shown that third-order aberrations associated with the quadrupole triplet can be compensated by adding an appropriate octupole. The code MOTER has shown that the required amount of octupole component can be considerably reduced by changing the first-order solution so that first-order and third-order terms are in opposition. The codes PATH and TRANSOPTR are being used to examine space-charge effects before the triplet.

The 180° Achromatic Bend

The codes TRANSOPTR, TRANSPORT, and PATH have demonstrated the dominance of the three-dimensional space-charge effects in the 180° bend. A matched achromatic solution is, in principle, achievable by increasing the strengths of the quadrupoles in each quadrant to compensate for the defocusing effects of space charge. The fourfold symmetry of the system will be lost, but a solution that minimizes the second-order aberrations may still be attainable. TRACE-3D has been the tool most applicable to this problem.

Development of Symplectic Integrators

An integrator is symplectic if it is equivalent to a canonical transformation of the particle coordinates from the initial state to the final state as derived from Hamilton's principle. Symplectic integrators are much better at eliminating numerically generated spurious changes in particle energy through the transport system. Symplectic algorithms for numerical integration of particle trajectories have been developed by Channell¹ and Ruth,² but can be implemented only for a special class of Hamiltonians, which unfortunately does not include the Hamiltonian for a relativistic particle in a magnetic field.

By a clever trick, we have been able to find an explicit symplectic scheme both for a particle in a static magnetic field and for a particle in an arbitrary electric field. In first approximation, these two integrators can be combined to produce a

symplectic integrator that will cover most cases of interest in magnetic optics. In addition, we have developed an explicit integration scheme for general "kick" Hamiltonians with three degrees of freedom.³ A kick Hamiltonian is one that is proportional to a delta function in time. By concatenating the results of such kicks, one can construct explicitly symplectic transformations general enough to approximate any known nonsymplectic transport scheme.

Fringe Fields of Permanent Magnets

The trend in design of accelerators for neutral particle beam applications calls for permanent-magnet quadrupoles and dipoles of the Halbach design.⁴ One such quadrupole is shown in Fig. 24. In multipole magnets, the high-order aberrations

Fig. 24. An example of a permanent-magnet quadrupole of the Halbach type. The magnet is built of many trapezoidal-shaped pieces of rare-earth cobalt magnetic materials, with magnetic orientation of each piece carefully chosen to produce the desired multipole field.

are produced in the fringing fields of the magnets. An accurate representation of the fringe fields is therefore important to the design of precision optical systems. We have computed, to seventh order, the fringe field of a Halbach-type quadrupole using the SMP computer algebra program. SMP automatically generated complete FORTRAN subroutines for inclusion in a code to integrate any particle trajectory

through the Halbach quadrupole. The integrator currently being used is the electromagnetic symplectic integrator described above. We are working on a representation of the fringe field of a Halbach-type dipole.

We have also developed an empirical expression for the axial dependence of the fringe field by using the known behavior that the field falls to half the value it would have if the quadrupole were semi-infinite in length, at a distance of one bore radius from its mechanical end. The field is expressed as a cubic polynomial. This simple form will be useful in any code, like PARMILA, that includes a representation of Halbach-type quadrupoles.

CALCULATIONS ON PSR COMMISSIONING

Early in the commissioning phase of the Proton Storage Ring (PSR), it was observed that, independent of initial beam current circulating in the ring, the beam current was decaying away with a lifetime of approximately 2 ms. The source of this decay is still not perfectly clear, but results from calculations indicate that scattering from the stripper foil in combination with some nonlinearity in the magnets has resulted in the loss of circulating protons. The stripper foil converts the neutral hydrogen beam to a proton beam at the point of injection into the ring. Unfortunately, the circulating beam must pass through the stripper foil until the ring is fully loaded. The energy loss of protons passing through the stripper foil is negligible, but each time a proton passes through the foil, it receives a small transverse kick.

Initial calculations were done using a simple linear mapping code.⁵ It used the beta functions calculated by another code and incorporated a simple exponential scattering law for the transverse kick caused by the stripper foil. The size of the effects depended on parameters (difficult to evaluate) in the exponential scattering law. The next step was to replace the exponential scattering law with a Monte Carlo algorithm (PSCAT), which better modeled the multiple scattering. The algorithm was checked analytically by solving the corresponding transport equation. The agreement between analytical and numerical results was fair. The Monte Carlo algorithm is very time-consuming; 2000 turns through a $1300 \mu\text{g}/\text{cm}^2$ aluminum foil takes 30 cpu minutes of CRAY time. The next improvement was to replace the Monte Carlo subroutine with a look-up table created with the Monte Carlo subroutine using the SUN computer. This decreased the calculation time by a factor of 10. The linear simulation code with Monte Carlo multiple scattering could simulate the experimentally observed loss rates by assuming that any proton whose

transverse displacement reached about 2.5 cm would be lost (see Fig. 25). There is no physical aperture at this amplitude. The smallest physical aperture is 4 cm, caused by the septum associated with the extraction system. This suggests that the aperture is "dynamical" rather than physical; that is, it is caused by some nonlinearity of the magnets. There is another reason to believe that the magnet system is not behaving as expected. The measured chromaticities ($\xi_x = -1.81$, $\xi_y = -1.13$) do not agree with calculated chromaticities ($\xi_x = -0.82$, $\xi_y = -1.31$).

Fig. 25. Loss curves for various assumed beam apertures. The simulation assumed 2000 initial particles with a Gaussian distribution within a beam size of 16 mm horizontally and 8 mm vertically. It is assumed that all particles, scattered by the stripper foil, that reach a transverse amplitude of $A(\text{mm})$ are lost. The curve for $A = 25$ mm is in best agreement with the measurements for the PSR.

By using the tracking code MARYLIE, it was found that the measured chromaticities could be obtained if there were a sextupole component of approximately 7 T/m^2 in one of the quadrupoles. MARYLIE also showed that this amount of sextupole would give the dynamical aperture suggested by the simple linear transport code. To date, no sextupole has been found in measured magnetic fields of the quadrupoles. The source of the nonlinearity, if it exists, is still unknown.

3-D RF CAVITY CODE DEVELOPMENT

AT-Division, in collaboration with DESY and KFA Jülich, is developing a 3-D rf cavity design code called MAFIA. This is part of the comprehensive work plan for 3-D code development, described in a previous report.⁶ The rf cavity code consists of a mesh generator M3, a resonator eigenvalue matrix generator R3, two types of eigenvalue solvers E31 and E32, and a postprocessor called P3. Working group meetings in December 1985 at KFA and DESY brought a new multigrid eigenvalue solver E32 into operation and more clearly defined the work plan for finishing MAFIA. The mesh generator M3 and the post processor P3 are being refined. The codes are being exercised on three specific problems: the LAMPF II cavity at Los Alamos, a "Jungle Gym" structure, and a waveguide-cavity junction problem at DESY. These test problems are probing the limits of the number of usable mesh points. Disk file size limits are being encountered. A redesign of the basic data file structure is being considered, both to cope with more mesh points and to allow more general data types.

LOS ALAMOS ACCELERATOR CODE GROUP (LAACG)

A preliminary users manual for the German ion-source code KOBRA has been completed.⁷ Work on the numerical algorithms and code improvements has begun.

The newly formed POISSON users' group and SUPERFISH users' group met in October at Los Alamos. They made three pages of recommended changes and enhancements to the POISSON/SUPERFISH design codes. Their list was prioritized, and we are in the process of responding to their recommendations while completing the documentation on these codes.

LAACG is now the distribution center for the code RAYTRACE, which was developed by Stan Kolwalski and H. Enge at the Massachusetts Institute of Technology. Requests should be mailed to

Distribution
Los Alamos Code Group
AT-6, Mail Stop H-829
Los Alamos National Laboratory
Los Alamos, NM 87545
(505)667-2839

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LAMPF II

TESTS ON 50- TO 60-MHz FERRITE-TUNED CAVITY

The LAMPF II accelerator will require an accelerating cavity tunable over a range of 50 to 60 MHz. The cavity chosen consists of a modified quarter-wave coaxial resonator loaded with microwave ferrites. The rf permeability of the ferrites (and therefore the cavity frequency) is varied by applying an external bias magnetic field perpendicular to the rf magnetic field.

A prototype aluminum cavity has been constructed, but it has not been loaded with ferrites. The following tests were performed on the unloaded cavity:

- Two rf-resistive loads were capacitively coupled to the cavity. The variation of the cavity Q as a function of the coupling capacitor size was measured.
- The frequencies of the lower TE and TM modes of the cavity were measured and will be compared with results of the URMEL 3-D cavity code that is being tested.
- The cavity was modeled as a two-port network. The cavity accelerating gap was considered one of the ports, and the point where the rf power amplifier connects was taken as the other port. Input impedances of each port were measured at very low frequencies. Also, the resonant frequencies of the cavity were measured for all permutations of open- or short-circuit boundary conditions at the two ports of the cavity. The results will be used as input for a two-port model of the cavity that is being developed. This model will predict the cavity impedance as a function of frequency and beam loading.

MEASUREMENT OF BEAM-COUPLING IMPEDANCE OF THE LAMPF II KICKER

Vacuum Chamber

The proposed LAMPF II accelerator will use ceramic vacuum chambers in the gap of the extraction kicker magnet. This ceramic vacuum chamber is covered by a matrix of fast recovery diodes (Fig. 26), which are forward biased by a dc current

Fig. 26. LAMPF II kicker vacuum chamber.

source. Because the rf impedance of a diode decreases as the dc bias current is increased, the diode matrix provides a low-impedance path for the ac beam image currents flowing on the vacuum chamber. When the extraction kicker magnet turns on, its fast rising magnetic field induces eddy currents in the diode matrix. When these currents exceed the dc bias current, some diodes will become back biased, which will prevent further build-up of the eddy currents, and the kicker magnetic field will penetrate into the vacuum chamber. The transverse beam coupling impedance of such a chamber (~ 75 cm long) was measured.

A 200- Ω balanced line was inserted into the test chamber. The rf transmission of this line was measured with a network analyzer (Fig. 27) and was compared with the transmission of the same line when it was inserted into a solid brass chamber. From the differences in the rf transmission (amplitude and phase), the real and imaginary parts of the transverse coupling impedance were deduced. The results are shown in Figs. 28 and 29 as a function of dc bias current and frequency.

Fig. 27. Transverse coupling impedance measurement setup.

Fig. 28. Real part of transverse coupling impedance of diode-shielded vacuum chamber.

Fig. 29. Imaginary part of transverse coupling impedance of diode-shielded vacuum chamber.

The measurements indicate that this diode-shielded chamber is a possible candidate for the LAMPF II kicker vacuum chamber, but that the transverse beam coupling impedance has to be lowered further. Efforts are under way to understand the results and to improve the characteristics of the chamber.

BEAR

STATUS

The purpose of the BEAR project is to conduct Beam Experiments Aboard Rockets. The primary objective of BEAR is to demonstrate the operation of a particle accelerator in space and, secondarily, to study the beam propagation phenomena of a neutral particle beam in exoatmospheric near-earth space. AT Division will provide the accelerator module for integration into a rocket payload for launch from White Sands Missile Range in late 1987.

The accelerator module is designed to provide 10-particle milliamperes of neutral hydrogen at 1-MeV energy. The accelerator module includes the following accelerator subsystems: (1) injector, (2) RFQ accelerator, (3) high-energy beam transport (HEBT), (4) neutralizer, (5) rf power, (6) vacuum system, (7) space frame, and (8) controls. The arrangement of items 1 through 4 in the accelerator module is shown in Fig. 30.

The accelerator subsystems are mounted on a central space-frame structure. The rf amplifiers and other electronic components are supported along this frame as well. The interfaces with the rocket are at either end of the space frame.

The injector is designed to present to the RFQ accelerator a 30-mA beam of negative hydrogen ions at an energy of 30 keV. The injector includes a Penning surface-conversion-type ion source designed to produce a 40-mA beam of H^- ions. This beam is transported to the entrance of the RFQ by a low-energy beam transport (LEBT), which includes a series of magnetic quadrupole lenses. The HEBT also includes a low-pressure xenon gas system that will ensure that the beam is fully space-charge neutralized. The purpose of the LEBT is to transform the beam characteristics from those produced by the ion source into those required for injection into the RFQ.

The RFQ is essentially a passive element from the point of view of payload integration. It is simply a resonant cavity having no moving parts, no beam diagnostics or controls, no cooling, and no vacuum pumps or gas components. It is designed to capture, bunch, focus, and accelerate 250 mA of beam to 1 MeV.

The 1-MeV beam is transported to the neutralizer by the HEBT. Like the LEBT, the HEBT consists of a series of magnetic quadrupole lenses to transform the beam characteristics from those produced at the exit of the RFQ to those required for the propagation experiment. The beam that enters the neutralizer is 2.5 cm in diameter and has a low divergence.

Fig. 30. Accelerator module and some subsystems.

The neutralizer is the final element on the beamline and is designed to convert approximately half of the incident H^- beam to H^0 . The neutralizer is a gas cell into which small amounts of xenon are pulsed just before each beam pulse. To prevent prestripping, the neutralizer is preceded by a cryotrap to condense any backstreaming gas after each pulse.

The vacuum system is designed to handle two major gas loads: (1) hydrogen from the ion source and (2) xenon from both the LEBT and the neutralizer. Getter-ion pumps will be used to pump hydrogen, whereas cryopumps will be used to pump the xenon. Pumping will be provided in the LEBT and HEBT regions only.

The rf power will be provided by two solid-state rf amplifiers that will be rigidly mounted to the space frame on the opposite sides of the RFQ. Power will be delivered to the RFQ by a pair of drive loops, each connected to its respective amplifier through a short section of flexible coaxial line. The output beam parameters of the BEAR accelerator are listed in Table II.

TABLE II
BEAR OUTPUT BEAM PARAMETERS

Ion	H ⁺
Energy	1 MeV
Current	10 mA
Beam diameter	2.5 cm
Beam divergence	± 2 mrad
Beam emittance	0.01π cm·mrad rms norm
Pulse width	50 μs
Pulse repetition rate	5 Hz

TEST STAND

The BEAR linac test stand (BLTS) is a laboratory facility whose mission is to test components and systems for the flight model of BEAR. Development of the BLTS experimental area began in September 1985. Significant progress has been made as follows:

1. The accelerator support structure has been designed, fabricated, and assembled. The alignment structures have been designed and fabricated.
2. Most of the required vacuum equipment has been procured, including one large turbomolecular vacuum pump, four cryogenic vacuum pumps, a vacuum leak detector, three fore-pump units, and the required isolation valves.
3. Design of the injector Faraday cage, high-voltage dome, and injector assembly is in progress. The isolation transformer has been ordered.

4. The central and instrumentation system is being designed. Two terminals and a microVAX computer have been delivered, and software development is in progress.

5. The permanent-magnet blocks for the HEBT and LEBT have been ordered. Design of the magnet holders is in progress.

Sufficient progress is being made in the BLTS to predict realistically the start of component tests by June 1986.

INJECTOR

Introduction

The BEAR injector, comprising the electronics package, ion source, and LEBT, will provide a low emittance 30-keV, 30-mA beam matched to the acceptance of the RFQ. Because the injector has to function during the launching of the rocket, extensive redesign of all components was necessary. We are being assisted in this by engineers from McDonnell Douglas Aerospace Corporation.

Ion Source

The Small Angle Source (SAS), as used on ATS, was selected as the ion source for this project. However, this source, in its present form, is unsuitable for this application, so an extensive redesign was undertaken. A cylindrical region 1 in. diameter and 1 in. long centered on the anode insert and including the extractor nose, slit, cathode, anode insert, and part of the anode was maintained as in the present design of the SAS—the rest of the source was completely redesigned. Some of the guidelines for the redesign were as follows:

- Improve the vacuum design: Move the magnets, heaters, thermocouples, and wires out of the vacuum. Reduce virtual leaks and area in vacuum.
- Improve the thermal design: Provide well-defined thermal paths and heaters in both anode and cathode.
- Easy assembly and replacement of components: Design the self-aligning components.

Detail design of the flight source is about half complete. One difficulty encountered in the thermal analysis was the lack of precise information about the heat loads on the anode and cathode. An engineering model that uses copper rods

rather than heat pipes to cool the anode and cathode is being designed to allow these measurements to be made.

A duplicate of the present SAS was fabricated for measuring discharge voltages and beam optics at 300 keV. During initial operation of this source without cesium, high H-minus currents (up to 65 mA) could be extracted. The discharge in this mode is very noisy and unstable and electrode erosion is high. However, the advantage of operating without cesium warrants further studies of this effect.

Injector Electronics and Control

A preliminary design of the electronics for the injector, both at -30 kV and at ground potential, has been completed; detailed design and breadboarding have been initiated. Major changes here are a high-frequency, transformer-isolated supply to provide power to equipment on the -30 -kV deck and a current-regulated arc pulser to reduce power consumption.

Low-Energy Beam Transport

An error study of the LEBT transport showed that the required positional and angular tolerances could easily be achieved with standard mechanical alignment. However, the transport is very sensitive to the degree of space-charge neutralization. Design of the quadrupole magnets is complete, and magnet blocks have been ordered. Final mechanical design of the LEBT has begun.

RFQ

The BEAR RFQ has been designed to accelerate 25 mA of H^- beam from 30 keV to 1 MeV. The numerical design was optimized with regard to both length and power while maintaining the peak surface field at a sufficiently conservative value. The final design was modified to lower the transverse and longitudinal current limits at the end of the accelerator section to the same 60-mA value as at the end of the gentle buncher, normally the critical constraint. This modification was accomplished by adjusting the modulation factor and stable phase while maintaining the minimum aperture. Although the transmission was lowered only slightly, the final overall length and total power requirement were both reduced by 10%. Some of the numerical design details are shown in Table III.

TABLE III
BEAR RFQ DESIGN PARAMETERS

W_i	Injector energy	30 keV
W_s	Energy at end of shaper	60 keV
W_g	Energy at end of buncher	186 keV
W_f	Final energy	1 MeV
ϕ_G	Synchronous phase at end of buncher	-40°
ϕ_F	Final synchronous phase	-34°
E_s	Peak surface field	37.3 MV/m
M_G	Modulation at end of buncher	1.78
M_f	Final modulation	2.28
a_G	Minimum aperture radius	1.20 mm
a_F	Final aperture radius	1.20 mm
r_o	Aperture radius at point of symmetry	1.71 mm
V	Intervane voltage	44 kV
L	Length	0.996 m
P	Power (at 30 mA)	67.4 kW
f	Radio frequency	425 MHz
T	Transmission	87%

The RFQ must be designed mechanically to be lightweight and to withstand the rigors of space qualification and rocket launch and still operate properly. Initial design studies showed that conventional design approaches would not meet the mechanical requirements. Preliminary studies indicate that vane position assembly tolerances can be relaxed while causing little degradation of beam quality. By not providing vane adjustments for tuning purposes, the assembly can be made very rigid to survive launch; rf tuning will be accomplished by custom machined, non-adjustable end cups, coupling rings, and tuning bars in each quadrant. A cross section of the monolithic RFQ design is shown in Fig. 31. The BEAR RFQ will be excited by drive loops in two opposite quadrants. It will be evacuated by vacuum pumps, located in the HEBT, through a slotted end plate in the high-energy end designed to be opaque to the rf fields but having good vacuum conductance.

Fig. 31. BEAR RFQ assembly flight model REF DWG 121-220002.

BEAM DYNAMICS

THE STATIONARY WATERBAG DISTRIBUTION

In 1970, Lapostolle¹ found for a round beam in a continuous focusing channel that a uniform filling of the interior of a constant Hamiltonian (energy) surface in 4-D phase space resulted in an analytic Bessel function solution for a stationary distribution. The distribution is generally called the stationary waterbag distribution. Such a distribution is important because it represents a more realistic analytic model of a stationary beam than the familiar K-V distribution.

Our interest in rms emittance and field energy has led us to re-examine the stationary waterbag distribution in a linear continuous focusing channel. We find that the beam density at high space-charge values has a uniform interior and a boundary thickness that is approximately equal to the Debye length.² We have numerically simulated the behavior of a beam with this distribution to show that in spite of its nonzero value of the nonlinear field energy, it shows no rms emittance change, consistent with its expected stationary and stable nature.

Emittance Growth; Comparison of Theoretical Studies and Simulation Results

In the last status report, we described initial work on generalized equations for the relationship between emittance and nonlinear field energy and for transfer of emittance between coordinate directions. We also reported on the development of a computer code for studying these energy and emittance transfer effects in the transverse (x-y) plane. This reporting period, we generated specific equations and predictions for x-y emittance transfer and growth and checked them with the code. We can now generate a physically sound estimate for the emittance changes in a continuous two-dimensional beam with different emittances and focusing forces in the two transverse directions.

The essence of the theoretical work is that there are two important mechanisms that affect emittance (barring external perturbations such as nonlinear focusing forces). The first, occurring on a relatively fast time scale, is the transfer of nonlinear electric field energy to transverse kinetic energy of the beam particles. The nonlinear field energy is a consequence of a nonuniform charge density within the beam; the particles are driven by the nonlinear field energy toward a more

uniform distribution, transforming field energy to kinetic energy. The second mechanism, which usually operates more slowly, is a transfer of kinetic energy from one coordinate direction to another. While superficially similar to equipartitioning of energy in a gas, it does not result from direct collisions between particles but from interactions of their individual or collective electric fields.

The simplest form of the transverse emittance equations is obtained by assuming that the final beam has uniform charge density, complete equipartitioning of kinetic energy has taken place between the x- and y-directions, and the rms size of the beam is constant. These assumptions have been found in the simulations to be quite accurate for a wide range of initial conditions. Then the ratios of final to initial emittances are given by

$$\frac{\varepsilon_{xf}}{\varepsilon_{xi}} = \left[1 - \frac{(P_i - 1)}{2P_i} + \frac{(1 + \frac{X}{Y})}{4P_i} \left(\frac{k_{oy}^2}{k_{yi}^2} - 1 \right) U_{ni} \right]^{1/2}$$

$$\frac{\varepsilon_{yf}}{\varepsilon_{yi}} = \left[1 + \frac{(P_i - 1)}{2} + \frac{(1 + \frac{X}{Y})}{4} \left(\frac{k_{oy}^2}{k_{yi}^2} - 1 \right) U_{ni} \right]^{1/2}$$

where P_i is the initial kinetic energy ratio X'^2/Y'^2 (the subscript i denotes initial values), X' and Y' being the equivalent uniform beam divergences; X and Y are the semiaxes of the equivalent uniform beam; U_{ni} is the initial nonuniform electric field energy. The term U_n depends upon the beam's charge distribution and is zero for a uniform beam; k_{yi} and k_{oy} are the betatron wave numbers in the y-direction of the equivalent uniform beam with, respectively, space-charge and zero current. For most of the problems in the simulations, $(\varepsilon_x/\varepsilon_y)_i = 4$, $(k_x/k_y)_i$ is 0.5 or greater, and k_{yi}/k_{oy} is usually greater than k_{xi}/k_{ox} . Although we have chosen to express the formulas in terms of k_{yi}/k_{oy} , the results can also be expressed in terms of k_{xi}/k_{ox} .

For an initial K-V (Kapchinskii-Vladimirskii) distribution, the results of the code simulations agree very well with the analytic expressions where equipartitioning is observed to occur; that is, for $k_{yi}/k_{oy} \lesssim 0.5$. Above this threshold, the simulated beams were stable, resulting in zero kinetic energy transfer. The code also gives information about the rate at which a particular problem converges upon the final conditions predicted by the formulas. Highly space-charge-dominated beams converge within one or a few plasma periods; for initial tune depressions close

to the threshold, convergence can take hundreds of plasma periods. I. Hofmann³ has predicted thresholds (agreeing well with the present results) above which a K-V beam will be stable and below which collective instabilities occur that can cause emittance transfer.

We believe that solving the x-y problem has yielded practical formulas for two-dimensional quasi-elliptical continuous beams and has also given us insight into the emittance growth mechanisms that we think will also occur for bunched beams. We intend now to progress to two-dimensional (r-z) bunched beams, a problem with significant practical interest.

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RADIO-FREQUENCY LABORATORY

BEAM-BREAKUP-RESISTANT STRUCTURES

Any accelerating cavity will have higher modes that can be excited by high beam currents. Some of these modes, for example, have magnetic fields across the chamber axis and can, therefore, give a deflecting force to beam particles as they travel down the axis. A desirable addition to a cavity would be some way of lowering the Q of the deflecting mode or modes with a minimal effect on the Q of the accelerating mode. Some practical difficulties encountered in two methods of lowering the Q of the deflecting mode were determined by an experiment in which a round aluminum cold model was set up that had the accelerating mode at 505 MHz and the first deflecting mode at 898 MHz. With care, the nominal Q s of these modes are reasonably reproducible in the 14 000 to 18 000 range.

Several short strip lines were constructed with a coupling loop at each end. Each line's first harmonic was tuned to the 898-MHz first deflecting mode of the cavity. By tuning and placing small resistors at high-current positions, the deflecting mode Q s were reduced from the 15 000 range down to the 100 to 200 range with less than a 10% effect in the accelerating mode Q . Plots of the transmission through the cavity were taken by small coupling probes as a function of frequency from 500 up to 2500 MHz with and without the strip line. These plots show many complicated and interesting effects on the many modes of the system. With the help of URMEL computer-generated field plots, several higher modes were identified by observing the mode frequency movement caused by insertion of metal rods in a multitude of holes in the cavity walls. Many higher mode Q s were also affected by the strip line. To understand the effects, the importance of the exact coupling method and its relation to the fields of each mode can be easily demonstrated.

A second method that used a waveguide also demonstrated a deflection-mode Q depression from the 17 000 range down to a few hundred with minimal effect on the accelerating-mode Q . A transmission spectrum with and without the waveguide was also taken for frequencies from 500 to 2500 MHz. This method consisted of modifying a standard waveguide by putting in a single ridge so that the cutoff frequency is near 600 MHz. With a single loop in the cavity connected to a loop in the waveguide, the waveguide acts as a high-pass filter above 600 MHz to pass higher mode power to a foam attenuator at the waveguide end.

Because of the multitude of modes and the complicated effects, it has become apparent that some method of easily selecting only the modes that are coupled to the beam would be desirable. To that end, the first attempt at using a balanced line down the axis of the cavity has been tried. The transmission down the line is attenuated by cavity modes that couple to it. The line itself reduces the 898-MHz cavity mode Q, but still the transmission went from -39 dB to -47 dB by attaching the waveguide.

CONSTANT VELOCITY DRIFT-TUBE LINAC CAVITY

An aluminum low-power model of a drift-tube linac cavity is in the process of being designed and constructed. The cavity will have equal-length drift tubes mounted on variable-length stems whose longitudinal position can be adjusted at will. Post couplers, whose longitudinal position can also be adjusted at will, will be provided also.

This structure will be used to study the mode spectra and field stabilization of drift-tube linacs. The periodicity of the drift tubes will make the theoretical understanding of this structure easier, and the movable drift tubes (and post couplers) will make structure modification easier.

The construction drawings for this structure are 95% complete, and some parts are being fabricated. A mechanical structure for doing perturbation field measurements on this structure has been constructed.

RFQ FIELD STABILIZATION

Several devices that could be used to stabilize the fields in RFQs have been tested; all are devices that would be internal to the RFQ. Figure 32 shows the devices as they would appear inserted into an RFQ. The devices are named to indicate the person who suggested them (either James Potter or Alvin Schempp). The devices are briefly described below:

- POTTER #1 - TEM line connecting two RFQ shorting rings (Fig. 33).
- POTTER #2 - TEM line attached to voltage taps half way up the sides of the RFQ vanes, taps alternating between adjacent vanes (Fig. 34).
- POTTER #3 - TEM line with "spider" loops alternating from side to side, loops ending on the RFQ envelope. (Fig. 35).
- SCHEMPP #1 - Inductively, series-loaded TEM line centered on RFQ quadrant (Fig. 36).

Fig. 32. Internal RFQ field stabilization devices tested and being tested.

Fig. 33. Potter #1.

Fig. 34. Potter #2.

Fig. 35. Potter #3.

Fig. 36. Schempp #1

The POTTER #1 and #2 devices were tested in an aluminum RFQ low-power model. A two-section #1 device stabilized the fields (Fig. 37). The #2 device was extremely difficult to tune, and no useful results were obtained because of this tuning difficulty and mechanical problems with the RFQ model.

Fig. 37. Test of two sections of Potter #1 stabilization scheme in aluminum RFQ cold model.

To simplify the testing of these devices, a radio-frequency dipole (RFD) was constructed (Fig. 38). The RFD consisted of a ridged waveguide terminated in end tuning sections so that it could be resonated at the waveguide cut-off frequency, and thus behave like an RFQ structure without the added complication of dipole modes mixing in with the quadrupole modes.

Single sections of the POTTER #3 and SCHEMPP #1 devices were tested in the RFD and showed field stabilization (Figs. 39 and 40).

Fig. 38. "RFD" radio-frequency dipole.

Fig. 39. First test of stabilization devices in dipole waveguide RFD.

Fig. 40. Test of Schempp #1 field stabilization device in rf dipole.

In addition, a four-section POTTER #3 device was tested that had $\lambda/4$ open end, $\lambda/4$ shorted end, and $\lambda/2$ detuned end resonators (Fig. 41) The device terminated in $\lambda/4$ open end resonators did not stabilize; the device terminated in $\lambda/4$ shorted end resonators stabilized only marginally at the ends. The $\lambda/2$ resonator terminated device gave the best results.

Efforts are under way to understand the operation of these stabilizing devices.

Fig. 41. Test of end boundary conditions of Potter #3 device in rf dipole.

P-BAR GRAVITY EXPERIMENT

ANTIPROTON RFQ DECELERATOR

A number of Los Alamos scientists, in collaboration with scientists at other institutions in this country and in Europe, have submitted a proposal for an experiment at the Low-Energy Antiproton Ring (LEAR) at CERN to measure the gravitational constant of antiprotons. The idea of the experiment is to decelerate and capture 5-MeV p-bars produced by the CERN proton synchrotron (PS) and stored in the low-energy accumulator ring. After capture, the p-bars will be cooled and then released vertically. Time-of-flight methods will be used to determine the effect of gravitational forces on the p-bars.¹ For this experiment, thermal velocities (~ 4 K) are required for the antiprotons. Antiprotons having kinetic energies of 5 MeV are available from LEAR. The proposal is to decelerate the antiprotons to thermal energies in several stages. The first stage uses an RFQ linac to decelerate the beam from 5.0 to 0.1 MeV. The second stage is an Energy-Shifter Cavity (ESC) to reduce further the energy to ~ 20 keV. The third and final stage is a series of pulsed ion traps using resistive-, potential-, and electron-cooling techniques.

AT Division is responsible for designing the system to decelerate the antiprotons to 20 keV. The 5-MeV injection energy is the dominating factor in the design of the deceleration system. Bunching at 5 MeV requires long distances. The acceleration (or deceleration) efficiency of RFQs decreases with increasing particle energy. A DTL is normally used for energies above 2 or 3 MeV. Also, the difficulty of tuning an RFQ increases with $(L/\lambda)^2$, where L is the length of the RFQ and λ is the free-space wavelength of the rf. However, we consider one relatively long RFQ to be a simpler system than an RFQ/DTL combination.

Design of RFQ

The major consideration in the design of the RFQ is to minimize its length. To accomplish this, the intervane voltage V must be as high as possible. However, if V is large, the mean aperture radius r_0 must also be large to prevent an excessively high electric field on the vane-tip surface. But r_0 cannot be arbitrarily large. A good rule of thumb is that $r_0 < \ell$, where $\ell = \beta\lambda/2$ is the length of the shortest cell in the RFQ. For 100-keV protons, $\beta = 0.0146$. Consequently, r_0 should be less than 0.007λ .

In the RFQ design, we have restricted the maximum surface field to $\hat{E}_s = \kappa V/r_0 \leq 1.65 E_K$, where E_K is the Kilpatrick limit, and κ is a field enhancement factor that depends on the vane-tip geometry:

We have assumed vane tips having a constant transverse radius of curvature $\rho = 0.75 r_0$ in order to minimize κ . The above considerations have led us to the RFQ parameters summarized in Table IV.

The matched input in the longitudinal phase space has $\Delta W/\Delta\phi = 5.65$ keV/deg. Assuming a total emittance of 100π keV·deg, a matched ellipse would have semiaxes of 4.2 deg and 24 keV. We have assumed the 5-MeV beam to have a transverse emittance of 3π ·mm·mrad, although the transverse acceptance of the RFQ is much larger.

TABLE IV
REFERENCE RFQ PARAMETERS

Parameter	Value
Frequency (MHz)	200
Initial energy (MeV)	5.0
Final energy (MeV)	0.1
Number of cells	84
Intervane voltage (kV)	177
Mean aperture radius r_0 (cm)	1.04
Peak surface field (MV/m)	24
Modulation parameter at 5 MeV	2.8
Modulation parameter at 0.1 MeV	1.1
Synchronous phase at 5 MeV (deg)	-162
Synchronous phase at 0.1 MeV (deg)	-142
Length (cm)	315
Peak power (kW)	535

Design of Buncher System

Using two buncher cavities, one operated at 200 MHz and the other at 400 MHz, it is possible to place about 75% of a continuous beam into the matched 100n keV-deg ellipse. Unfortunately, the distance required at 5 MeV is about 25 m. However, it is possible to bunch 50% of the beam into a smaller phase spread in a distance of about 13 m. This beam is not longitudinally matched to the RFQ but approximates a vertical line in longitudinal phase space. By slightly adjusting the intervane voltage, this line can be made almost horizontal at the exit of the RFQ, which means that the beam can have a small energy spread.

Design of ESC

The design of the Energy-Shifter Cavity has not been completed and may present the major challenge. The deceleration gap must be very short because of the low energy of the particles, but must be long enough to allow the voltage across the gap to be about 100 kV without sparking.

SIMULATION OF THE CAPTURE PROCESS

Simulations of the capture process in the Penning trap have been done. The geometry of the trap is shown in Fig. 42. Longitudinal confinement is provided by the parabolic electric potential along the beam direction (z-axis). The transverse confinement is provided by a 6-T solenoidal magnetic field and a nonuniform transverse electric field. The main object of the calculations is to determine the time dependence of the longitudinal electric field. Three schemes have been devised to trap the p-bars in the Penning trap. The time dependences of the voltages are compared in Table V. The turn-on and turn-off times and the voltages have been determined by doing parametric studies using the simulation program. The first scheme has large voltages and short rise times. The second and third schemes may be practical. Further work is planned.

Fig. 42. Geometrical arrangement for the proposed Penning trap. The 20-keV p-bars enter the bottom electrode and are reflected by a rising electric field at the top electrode. By the time that they return to the bottom electrode, the field there has risen also. This will trap approximately 10^9 p-bars. Radial confinement is provided by a 6-T solenoidal magnetic field.

TABLE V
TIME DEPENDENCE OF END-CAP VOLTAGES

Scheme 1 ^a		Scheme 2 ^b		Scheme 3 ^c	
Time (ns)	Voltage (kV)	Time (ns)	Voltage (kV)	Time (ns)	Voltage (kV)
0.00	0.0	0.00	19.0	0.0	0.0
486.1	$V_0(t-486.1)$	463.34	$V_0(572.04-t)$	486.1	$V_0(t-486.1)$
>521.9	200	572.04	$V_1(t-572.04)$	516.1	25
		>672.04	10		

^a V_0 is 200 kV/35.8 ns

^b V_0 is 19 kV/108.7 ns; V_1 is 10 kV/100 ns. There is a flat plate at ground potential 1 cm in front of the upstream end cap.

^c V_0 is 25 kV/30 ns. The downstream end cap is held at 25 kV, and the given time-dependent voltage is applied to the upstream end cap.

STORAGE IN CONDENSED MATTER

A simple one-dimensional model of an ionic lattice was used to see if p-bars could be substituted for the negative ion. Ionic lattices would be unstable if the only force acting were the Coulomb force. The lattice is stabilized by the so-called exchange forces between valence electrons. The p-bar has no shell of electrons to stabilize it in the lattice. We were able to show that a p-bar could be stabilized at the negative ion sites by the lattice vibrations of the material. This is a form of dynamic stabilization familiar in rf quadrupoles and rf Penning traps. Stabilization requires laser stimulation of the zone-center optical phonon in the lattice. The model is too simple to represent reality. Some preliminary work has been done on three-dimensional lattices, showing that if the p-bar finds itself at a negative ion site it will see a harmonic potential that is proportional to x^4 .

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U OF ILLINOIS RACETRACK MICROTRON

SOFTWARE DESIGN

The overall architecture for the Cascade Microtron (CCM) control system has been accepted by the Nuclear Physics Laboratory (NPL) of the University of Illinois. The design has been finished in sufficient detail to permit NPL staff to take over and complete the system. Design notes and documents are being completed and reviewed as NPL assumes responsibility for the remaining work.

The CCM control system uses a shared-memory database architecture similar to that of the Proton Storage Ring (PSR) control system. In this scheme, application programs can control pieces of equipment by writing values into a database; separate software is responsible for transferring database values to the actual equipment.

The CCM control system comprises several microcomputer-based nodes. Each basic node is a stand-alone control console. The nodes are organized into a local area network (LAN) that allows each node to have access to data in the other nodes. The design permits the addition of a master console node that has control of the entire system.

ACCELERATOR STRUCTURE

The second accelerator structure, the capture accelerator, was fabricated and delivered to the University of Illinois in early February 1986. In addition to the 17-cavity accelerating structure, the accelerator support and alignment structure and the accelerator cooling system were fabricated and delivered.

Work has begun on the third University of Illinois accelerator structure, the preaccelerator, consisting of 45 accelerating cavities. The fabrication techniques for these types of side-coupled structures are so far advanced that a majority of the fabrication and tuning of the preaccelerator structure will be done in commercial machine shops, with Laboratory liaison.

NBS MICROTRON

In February the 8-m-long main microtron accelerator was delivered and installed by Los Alamos personnel at the National Bureau of Standards (NBS). The installation included alignment and vacuum and water system tests. The accelerator will now be connected to the rf power distribution system by NBS for power conditioning. The installation of this linac completes the deliverables of the original collaboration agreement. Los Alamos looks forward to assisting NBS in commissioning the microtron with beam as soon as the high-voltage power supply problems are solved.

RFQ VANE MACHINING SOFTWARE

Software development for RFQ vane-tip machining has been performed. Various test procedures have been proposed and tested. Some of the work is currently in progress and is expected to continue as new RFQ designs are developed.

MICROWAVE AND RF TECHNOLOGY

VERY HIGH POWER MICROWAVE SOURCES

The Microwave and RF Technology Group is concerned with developing very high power microwave systems. The effort encompasses joint work with several other divisions of the Laboratory. The successful design and construction of useful systems for pulsed power, microwave sources, diagnostics, and propagation require the broad base of expertise available throughout the Laboratory. During the last six months, we have made significant progress towards establishing the utility of very high power microwave systems to resolve near- and far-term DoD and DOE issues. This effort has culminated in Los Alamos being identified as the primary Laboratory to build prototype systems for the Air Force and being identified as the primary effects-testing agency for a Laboratory/DOE Project. Some particular areas of progress are listed below.

- The electron-beam-driven, virtual cathode oscillator, microwave source has become operational. The electron beam is produced by a Blumlein-driven diode with a field emission cathode, and microwaves have been produced in a reflexing electron geometry. The oscillation frequency is predominantly at the plasma frequency of the electron beam, and the effect of using resonant structures is being studied. A copper microwave cavity has been installed on the beamline with an unloaded Q of approximately 1000 in the TM_{010} mode. This mode occurs at about 1 GHz. Preliminary results indicate that microwave power is being produced at the level of tens of kilowatts at a frequency of 1 GHz. Steps are being taken to fabricate better diagnostics for power and frequency measurements. Also, electron-beam diagnostics are being improved to give reliable voltage and current information on the electron beam.
- We have recently completed an extended Vulnerability, Lethality, and Countermeasures (VL&C) test program in collaboration with Army and the Air Force participation. Personnel from the Medium Energy Physics Division have been continuously involved in this effort and have helped to make this a successful project.

- The permanent-magnet technology that has been developed for beamline focusing optics has found a new application. A flux compressor has been designed in a joint effort with personnel from the Shock Wave Physics Group (Dynamic Testing Division) for use in an initial test series. The permanent-magnet assembly will provide the initial magnetic field to a flux compressor. The detonator system may be located within one of the two magnet pole pieces to use the entire generator length effectively.
- The 1.3-GHz klystron rf system has been installed. Before klystron operation can begin, two major projects must be completed: install the 208- and 480-Vac power and provide the necessary cooling water. Once the utilities are available, this klystron station will be available for the high-current free-electron laser gun project, the VL&C tests scheduled for the summer, and for the phase injection locking experiments for new, very high power microwave sources.

FMIT RF SECTION

The Fusion Materials Irradiation Test (FMIT) rf section is charged with the operation, maintenance, and upgrade of the FMIT rf accelerating system. The present system consists of a 75-keV injector, and 2-MeV RFQ. This section contributed 150 hours of run time of the system, as required by the FMIT operations program. This time included RFQ conditioning and beam acceleration requirements. The balance of our efforts was spent on operations support and work on the second amplifier system.

We are near completion of setup for a pulsed high-power test of the second amplifier chain into a shorted transmission line. Success there will mean we are ready to connect to the RFQ for final setup and testing of the second rf amplifier system. Completion of these tests will enable us to perform two loop-drive operations of the FMIT RFQ, time and accelerating system permitting.

LANGMUIR-PROBE DATA-ACQUISITION SYSTEM

A system was built to ramp a Langmuir probe between -50 and +50 V in 2.5 -V increments and to record the ramp voltage and the voltage drop in a resistor in series with the probe. The system consisted of a small PDP-11 configuration with a DSD-440 floppy disk and CAMAC hardware.

The ramp voltage is supplied to a locally built amplifier to convert the ± 10 -V signal from a CAMAC digital-to-analog converter to the ± 50 V required by the probe. This voltage and the voltage across the series resistor (through an optical isolator) are measured by a CAMAC analog-to-digital converter and recorded on a floppy disk for later processing. The operating system is DEC's RT-11, and the programs were written in FORTRAN.

FMIT CONTROL SYSTEM

Programs used in the control system were modified to correct errors. Console displays were enhanced to give the operator more information or to allow quicker access to other displays. This maintenance required additions to the database.

Other FMIT software maintenance consisted of modifications to the alarm code and addition of a variety of utility routines. All but an error-message interpreter routine were completed. The latter effort was abandoned when the project was terminated.

PROTON STORAGE RING

INTRODUCTION

This period encompassed the final three months of the initial Proton Storage Ring (PSR) commissioning cycle that ended December 22, 1985. The results of this commissioning program have shown (with one important exception) that PSR works about as expected and have given us confidence that design goals will be reached in timely fashion. The ring has been operated for neutron users at 30 μ A (nearly one-third the design average current), although with significant beam losses, and has accumulated 2.6×10^{13} protons (half the design charge per pulse). These are major accomplishments for the first year of commissioning.

Considering the extrapolations into new performance regimes that had to be made during PSR design, we are happy to see that there seem to be no fundamental physics obstacles to reaching full performance. However, there has been one large surprise, namely the greater-than-anticipated beam loss from scattering in the stripper foil. The root cause of this unexpected phenomenon has still not been identified, although several pieces of evidence now point to a reduced effective (dynamic) aperture arising from a magnetic field anomaly somewhere in the ring lattice.

FOIL SCATTERING QUESTION

There is an overwhelming body of data telling us that the effect of scattering in the PSR stripper foil is much stronger than predicted. Loss rates are directly proportional to stripper material thickness, and the measured beam lifetime is inversely proportional. The general shape of the beam survival curve is what would be expected from a model in which the emittance grows linearly with the number of foil traversals, assuming multiple coulomb scattering is the dominant interaction.

Neither a linear nor a nonlinear simulation model of the ring lattice (without errors) can replicate the experimentally measured lifetimes unless the effective or dynamic aperture is reduced to something like 2 cm (half-width). The minimum known physical restrictions are 4 cm half-widths at the extraction septum and one orbit bumper. For this dimension, the beam lifetime from scattering in the foil is calculated to be 5-10 times greater than what we measured.

However, the nonlinear simulation can produce strikingly different results if a sizable field error is included in the lattice description. Using an error sextupole

whose magnitude is consistent with the chromaticity measurements (discussed below), the nonlinear simulation (MARYLIE) has shown that protons with starting betatron amplitudes greater than 2 cm can be rapidly pushed beyond the physical aperture. The effect is apparently due to the complicated interplay between the scattering process at the foil and the nonlinear field error. Given identical starting conditions, the particle trajectory remains well within the physical aperture when either (1) the field error is enabled, but the scattering is turned off or (2) the field error is disabled, but the scattering is turned on.

Results from the nonlinear simulations with field errors are only suggestive so far, and much more work remains to be done to obtain a clear picture. However, these results do lend support to speculation that the effective or dynamic aperture in the PSR may, in fact, be reduced well below the physical aperture by field errors.

CHROMATICITY ANOMALY

Measurements of the lattice chromaticities (x and y) produced values that disagree markedly with those calculated from MARYLIE (and, independently, those calculated by an analytic method). Although both chromaticities were negative, as expected, the magnitude in the x-plane was twice that predicted, and the magnitude in the y-plane was about 30% less than predicted.

These results strongly suggest some kind of magnetic anomaly in the ring lattice, producing a large sextupole field error. The kind of problem that would best reproduce both x and y measurements is a sextupole error in one or more of the F-quadrupoles. The fringe fields of the extraction septum magnets are also problem candidates, but do not fit the data quite as well.

A preliminary check of the quadrupole coil resistances has turned up nothing significant. We also removed the quadrupole field clamps and made a physical inspection (looking for wrenches or other steel objects lying between coils, for example) and then a Hall-probe measurement of the variation between fields at the poles of each unit. The magnitude of the postulated sextupole error is large, 8-13 T/m² (depending on location). Nothing approaching this level was found.

INSTABILITY AT HIGH ACCUMULATED CHARGE LEVELS

By careful adjustment of various storage ring parameters, we were able during the high-current beam studies to accumulate 2.6×10^{13} protons per pulse (ppp), possibly a record for circular machines in this energy range. We observed that rapid

beam loss ($< 100 \mu\text{s}$ to lose half the beam) can occur at this charge level (and well below it) if the machine parameters are incorrectly adjusted. Parameters that most strongly affected the amount of charge that could be held without instability were the beam cross section and buncher rf voltage. The bigger the beam size and the higher the rf amplitudes, the greater the charge level that could be reached, a clear indication of space-charge effects.

Whether the sudden beam loss that has been seen represents a coherent (impedance-related) instability or something else is unclear at the moment, given the relatively small amount of data so far obtained and the somewhat conflicting observations. The 200-MHz position monitors have provided some indication of transverse coherent beam motion occurring at or just preceding the time of heavy beam loss. The apparent rise time of this motion is about $20 \mu\text{s}$, which is extremely fast. Theory predicts stability for transverse coherent oscillations below mode number 10 if the chromaticity is negative (which it is), at least for a purely resistive wall impedance. Consultants from CERN with whom the data were discussed feel that the observed rise times are much too fast to be believed. They expect something like several-hundred microseconds at worst.

An alternative explanation for fast beam loss could be that the sharp bunching of the beam produces an incoherent Laslett tune shift greater than 0.25 in the center of the bunch, placing a sizable fraction of the beam on the integer resonance $Q_y = 2.0$. This bunching could also lead to fast loss of a large fraction of the beam. The main problem with this explanation is that in such a picture one would expect beam intensity to be limited at some asymptotic level as accumulation proceeds (and as particles move onto the integer resonance line), rather than a sudden reduction in intensity.

At the moment we feel there is insufficient evidence for a wall-type coherent instability. If it is really present and, in fact, does have the rise time observed, a rather high-power damper would be required for adequate suppression. Given the experimental uncertainty, and also the fact that 5.2×10^{13} ppp probably cannot be produced (by the H^- ion source) for the 1986 run cycle, we believe the prudent course of action is to defer construction of a damper until more data have been obtained in the 2 to 4×10^{13} ppp range.

CONTINUATION OF PSR COMMISSIONING IN 1986

The emphasis in 1986 for storage ring improvements will be on the following:

1. Implementation of improved diagnostics that will allow detailed investigation of

high-current phenomena, including coherent motion of the beam over a wide frequency range, tune spread and tune shift, and beam profile evolution during accumulation

2. Installation of hardware that will allow great flexibility in control and manipulation of transverse and longitudinal space-charge density. Such devices include those listed below:

- Sextupoles for correction of chromaticity and suppression of $1/3$ integer resonance lines just above the PSR nominal operating point; this will provide more room in the tune diagram above the dangerous integer lines.
- Second and third harmonics added to the buncher waveform. These will help spread the bunch longitudinally, thereby reducing the peak transverse space-charge density.
- A larger vertical orbit bump, to spread the beam more uniformly and over a larger area in transverse phase space.

3. Continuing investigation of the foil scattering and chromaticity anomalies (which appear to be related). This involves two basic paths:

- Simulation with a nonlinear PSR lattice, including postulated sextupole errors and foil scattering. The calculations need to be extended to consider several possible sources of error, and enough particle runs need to be made to build up a good picture of the expected transverse distributions and beam lifetime for different conditions.
- Careful inspection of the PSR magnetic elements and a thorough search for magnetic or other anomalies in the ring lattice.

4. Reduction and management of losses in the ring. There are several paths for addressing this problem. Of course, if a magnetic error is found in the lattice, its correction most likely would immediately yield a large reduction in the foil scattering losses. Failing a solution to this puzzle, there are several other avenues to be followed:

- Control of losses by a beam scraping system in the ring.
- Increasing the beam intensity from the linac.
- Reduction of stripper foil thickness and suspension of the stripping arc on a very thin backing.
- Improvement of the orbit bumper system.
- Better extraction diagnostics to permit more exact adjustment of longitudinal and radial beam location at extraction time.
- Elimination of known aperture restrictions.

PHOENIX PROJECT

INTRODUCTION

The Phoenix Project, located at Los Alamos National Laboratory technical site TA-55, involves isotopic enrichment of nuclear materials using a photochemical process. It is an experiment facility to develop techniques that can be scaled and used in a large plant. The Phoenix control system routinely monitors about 250 binary and analog signals associated with the operation of the process gas-flow loop. This system has performed reliably and has become an essential component of everyday flow-loop operation. Work has begun on providing for the capability to use the system for monitoring about 500 laser-control and diagnostic signals as well.

PHOENIX CONTROL-SYSTEM ENHANCEMENTS

The control system is an integration of a commercial, distributed-process control system and a general-purpose UNIX host computer. A recent joint effort between personnel of the NPB Control/Automation Group and the vendor of the commercial-process control system has resulted in the capability for modifying any part of the commercial software from the host computer. With this capability we are able to incorporate enhancements and fix software bugs as they are discovered. Recent enhancements to the system include an order-of-magnitude increase in the host-to-system parameters, a technique for archiving data from process runs, development of a timing and triggering system for synchronizing various experimental process events, and interfaces to intelligent gamma counter and gamma spectrometer instrumentation.

OPERATIONAL NOTES

A number of hardware and software problems have been fixed. A software revision control system has been implemented so that software modifications can be automatically tracked. A computer system security plan has been written and is in the final stages of approval so that classified operation of the system may begin soon.

LASER ROOM UPGRADE

Control and monitor computer assignments have been re-evaluated for both the Selective and Dissociative laser installation. Dissociative laser field wiring has been updated and installed with preliminary check-out. Control system database entries are complete and include special algorithms for beam diagnostic signal calibration. Dissociative laser subsystem displays are complete and reflect all currently installed data points. Modification for the Selective laser installation has begun. Field wiring design is complete and field boxes are being fabricated. Front-end signal preprocessing hardware is being designed to extract rate, separation, and peak information from output laser pulses.

Final shutter and warning light systems have been designed and delivered for the process and Dissociative laser rooms. The Selective laser room subsystem has been designed and fabrication is in process.

DISTRIBUTED COMPUTER SYSTEM

INTRODUCTION

A design for an upgrade to the existing accelerator test stand (ATS) computer system has been completed. Orders have been placed for the appropriate hardware and software for a fiber optic network. Standard Ethernet components capable of TCP/IP and DECnet are being used. The network will connect all microVAXes and the existing VAX 11/750 and will allow remote file transfer and remote log-in. Fiber optics was chosen because of potential problems with electromagnetic interference.

A CAMAC crate controller configuration was chosen that uses a 2060 serial highway driver at each microVAX and an existing type L-2 serial crate controller at each crate. This configuration allows DMA capability from each crate on the serial highway. It uses a device driver that is already written, thus reducing the cost of software development.

Existing software is being catalogued and documented. Work is under way to rewrite and clean up certain heavily used programs to make future modifications and upgrades easier.

RF CONTROL DISPLAYS

An operator interface program is being developed for the rf control subsystem. The following menu selections are available to the operator:

A. Start-up	H. Delays and Widths
B. Shutdown	I. Amplitudes, Phases, Slugs
C. Q Power	J. High Voltage and Power Supplies
D. RFQ Amplitude	K. Interlocks
E. Timing Pulses	L, N, & O (Reserved)
F. Knob Assignments	M. Main Menu
G. Pickup Loops	P, Q, R, S, T, & U (Not Used)
	X. Exit Program

The "start-up" and "shutdown" procedures are not yet completely defined in enough detail for program development. The other displays and the associated functions are operational at the limit of the current state-of-hardware connections. A great deal of testing remains to be done when additional hardware is available and after all hardware is checked out.

Because changes will undoubtedly be required in some hardware and software, the software was developed so that future modifications will be simplified.

KrF PROJECT

INTRODUCTION

The NPB Control/Automation Group's responsibilities to the Aurora laser fusion project are bifold. We are to provide on-going operational hardware and software to the project. We are also required to complete the controls design application to provide the control support tools needed to control and diagnose the KrF laser system. To that end, the PDP 11/34 data-acquisition system is operational; the Tektronix Physics Diagnostic system is 90% complete; the third and last machine interface (for front-end and small-aperture module control and diagnostics) has been checked out; changeover to a local PDP 11/60 is complete; and the software for an integrated shot is ready. An in-depth description of the control system on this project has been written.¹

THE 11/34 SYSTEM

The 11/34 is set up and acquiring data in an "intermediate" mode. Until the laser subsystems are working together as an integrated system, more information is often needed than is necessary to bring up an amplifier for its routine operation. This need has mandated configuring the data-acquisition system in a flexible regime for some unique D/A requirements, rather than what was called for in the original work package.

Several changes have been made to the software to allow for easier operation. A preliminary operating procedure has been drafted and is in use.

TEKTRONIX SPS SYSTEM

The high-speed data-acquisition capability has been usable since about August 1985. Some "fixes" on the purchased software have since been performed by the vendor to correct some minor difficulties. The vendor is now revising some of the software to make it more user friendly.

The software driver for the low-speed CAMAC digitizers is three-fourths done. Integration of this driver into the main software package is under way.

SIGNAL MULTIPLEXING

A signal-switching device has been purchased that can multiplex 90 input lines into 15 output lines, thus providing more flexibility in acquiring signals, more efficient usage of the available digitizing capacity, and an economical and timely solution to the shortage of screen-room feedthroughs. This system is capable of immediate expansion with the purchase of additional plug-in boards; is programmable for preset switching patterns; can handle a variety of signals from dc high-current to microwave; and is manually, remotely, and computer controllable.

The initial function test has been done on the switcher with insertion into data-acquisition system to start soon.

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AT-1 TECHNICAL MEMOS AND NOTES

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L. Young	Comparison of Deflecting Structures to Accelerating Structures for Beam Splitting	AT-1:85-347	10/04/85
T. P. Wangler C. E. Griffin	An RFQ Beam Dynamics Design Study for BEAR	AT-1:85-348	10/04/85
T. P. Wangler R. H. Stokes	High-Current, High-Brightness Particle Beams	AT-1:85-397	11/05/85
M. R. Shubaly C. Dillow L. D. Hansborough J. D. Sherman K. Prince	The BEAR H-Injector	AT-1:85-434	12/31/85
T. P. Wangler	RMS Emittance, Field Energy, and Energy Flow	AT-1:86-1	01/08/86
T. P. Wangler K. R. Crandall	Characteristics of the Stationary Waterbag Distribution	AT-1:86-4	01/10/86
L. Walling P. Friedrichs G. Spalek	Transverse Coupling Impedance of the LAMPF II Biased-Diode-Shielded Ceramic Vacuum Chamber	AT-1:86-22	01/29/86
K. R. Crandall T. P. Wangler	SSC Injector Example	AT-1:86-27	02/03/86
K. R. Crandall C. E. Griffin	BEAR Error Studies	AT-1:86-33	02/06/86
M. Reiser	Current and Phase-Space Density Limits of Ion Sources	AT-1:86-45	02/18/86
J. Billen S. Hassemer D. Kingsbury	Effect of Tuning Bars in the Ramped Gradient Drift-Tube Linac	AT-1:86-70	03/06/86
R. H. Stokes	Lathe-Tuned Poles for Multiple-Channel RFQ Accelerator Arrays	AT-1:86-71	03/06/86

<u>Authors</u>	<u>Title</u>	<u>Symbol</u>	<u>Date</u>
T. P. Wangler	Emittance Growth for 2-D Charged Particle Beams Including Equipartitioning and Nonlinear Field Energy Effects	AT-1:86-72	03/12/86
E. Boltezar	Cold Model for BEAR RFQ	AT-1:86-82	03/13/86
G. Spalek L. Walling	Results of Measurements on LAMPF II Cavity Modelled as Two-Port Network Cavity Not Loaded with Ferrites	AT-1:86-88	03/18/86
E. Gray D. McMurry	Photocathode Probe RF Contact	AT-1:86-99	03/24/86
E. Gray A. Shapiro J. Browman	More Experiments on Beam-Breakup-Resistant Cavities	AT-1:86-100	03/25/86

AT-3 TECHNICAL MEMOS

<u>Authors</u>	<u>Title</u>	<u>Symbol</u>	<u>Date</u>
W. L. Rogers	PSR Programmable Controller	AT-3:85-127	12/85

AT-6 TECHNICAL MEMOS AND NOTES

Authors	Title	Symbol	Date
J. L. Warren	Forces and Torques on Matter in Fields	AT-6:ATN-85-8	9/85
T. S. Wang	Preliminary Theoretical Studies of RF Equilibria and Stability	AT-6:ATN-85-9	NA
W. P. Lysenko	Particle-in-Cell (PIC) Codes	AT-6:ATN-86-1	1/86
A. J. Dragt and R. D. Ryne	Use of MARYLIE to Compute Second and Third Order Aberrations	AT-6:ATN-86-2	1/86
P. J. Channell	Symplectic Integration for Particles in Electric and Magnetic Fields	AT-6:ATN-86-5	1/86
P. J. Channell	Explicit Integration of Kick Hamiltonians in Three Degrees of Freedom	AT-6:ATN-86-6	4/3/86
E. A. Wadlinger	Heavy Ion RFQ Properties	AT-6:ATN-86-7	4/3/86
P. J. Channell	Possibility of a Two-Stream Instability with a Foil Neutralizer	AT-6:ATN-86-9	4/7/86
J. Lamoureux, J. Browman, and G. Spalek	Damping Deflecting Modes in Accelerating Cavities	AT-6:ATN-86-10	4/86
J. L. Warren and M. H. Foss	Stacking Factor and Permeability Extrapolation Corrections to POISSON, PANDIRA, and MIRT	AT-6:ATN-86-11	4/86
R. D. Ryne	Numerical Computation of Transfer Maps Using Lie Algebraic Methods	AT-6:ATN-86-12	NA
J. L. Warren	Group Theoretical Simplification of Magnetostatic Potentials in Two Dimensions	AT-6:ATN-86-14	NA
G. P. Boicourt	Proton Orbits in Ion Trap	AT-6:85:155	10/07/85
G. P. Boicourt	Another Possibility for P or P[Bar] Injection	AT-6:85-156	10/23/85
G. P. Boicourt	P[Bar] Injection Method 3	AT-6:85-160	10/25/85
G. P. Boicourt M. C. Vasquez	Cubic Ramping from 2.0 MV/m to 5.1 MV/m	AT-6:85-168	11/05/85

<u>Authors</u>	<u>Title</u>	<u>Symbol</u>	<u>Date</u>
G. P. Boicourt M. C. Vasquez	SF Data Tables for SP/Star 1 DTL Front End	AT-6:85-170	11/08/85
G. P. Boicourt M. C. Vasquez	Smooth Fringe Model for Hybrid Quads	AT-6:85-173	11/18/85
G. P. Boicourt M. C. Vasquez	Power Distribution in a Ramped DTL Tank	AT-6:85-174	11/18/85
G. P. Boicourt M. C. Vasquez	A Second Field Model for Hybrid Quads	AT-6:85-197	12/13/85
G. P. Boicourt M. C. Vasquez W. B. Cottingham	PARMTEQ Results Using Measured Input Beam from Runs 404 and 405; Detailed Dependencies of Transverse and Longitudinal Phase Space on Vane Voltage	AT-6:86-11	01/21/86
G. P. Boicourt M. C. Vasquez	100 MeV, 450 MHz Cavity: Calculated Axial Field Corresponding to Measured Q and Power at Room and Liquid Nitrogen Temperature	AT-6:86-21	02/06/86
G. P. Boicourt M. C. Vasquez	PARMTEQ Calculations of FMIT RFQ Performance Using Latest Measured Input Values	AT-6:86-24	02/11/86
G. P. Boicourt M. C. Vasquez	Information on PARMILA Sent to Grumman Aerospace	AT-6:86-33	02/26/86