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LA--10118-SR

DE84 015052

Accelerator Technology Program

July—December 1982

Compiled by
R. A. Jameson

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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ACCELERATOR TECHNOLOGY PROGRAM

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ABSTRACT

Major projects of the Los Alamos National Laboratory's Accelerator Technology Division are discussed, covering activities that occurred during the last six months of calendar 1982.

The first sections report highlights in beam dynamics, accelerator inertial fusion, radio-frequency structure development, the racetrack microtron, CERN high-energy physics experiment NA-12, and high-flux radiographic linac study.

Next we report on selected Proton Storage Ring activities that have made significant progress during this reporting period, followed by an update on the free electron laser. The Fusion Materials Irradiation Test Facility work is discussed next, then progress on the klystron development project and on the gyrocon project. The activities of the newly formed Theory and Simulation Group are outlined. The last section covers activities concerning the accelerator test stand for the neutral particle beam program.

BEAM DYNAMICS

RFQ VANE-TIP GEOMETRY SYSTEMATICS

A study of five types of radio-frequency quadrupole (RFQ) vane-tip geometries has been made.^{1,2} One geometry type, which corresponded to the geometry for proof-of-principle (POP) experiment, used an ideal two-term potential function to describe both the longitudinal vane-tip profile and the transverse radius of curvature at the vane tip. Two geometry types assumed the two-term potential function for the longitudinal profile, but had values for the transverse radius of curvature ρ that were constant throughout the cell; $\rho = 0.75 r_0$ and $\rho = r_0$ were studied, where r_0 is the radius at the point of quadrupole symmetry. Two other geometry types used a sinusoidal longitudinal profile with $\rho = 0.75 r_0$ and $\rho = r_0$, respectively.

For each geometry choice, the program CHARGE-3D was used for the three-dimensional calculation of the potential and electric-field values throughout the cell, given a cell aspect ratio r_0/L and a modulation parameter m . These calculations yielded the peak surface electric-field values and the various multipole components for a general expansion of the potential. The results of these three-dimensional analyses were reported in tabular form.

Important advantages such as shorter linacs and higher current limits can be gained by having high electric-field intensities. On the other hand, the peak surface field must be kept below the sparking limit, and for some applications, the fields from higher order multipoles must not deteriorate the beam quality. This study has shown that the peak surface field can be reduced by using a constant transverse radius of curvature, which also allows use of a special cutting tool that could greatly reduce machining time. For some cases, the sinusoidal profile requires a smaller increase in the modulation required to obtain a given accelerating field, which may be an advantage, when machining shorter cells. Detailed beam-dynamics simulations of a given RFQ are needed to evaluate the effects on the beam from higher order multipoles.

IMPROVED RFQ RADIAL-MATCHING SECTION

In the RFQ radial-matching section, the aperture is tapered so that the quadrupole field rises from zero to its full value over several rf periods.

This procedure allows the time-independent beam to adapt itself to the time-dependent focusing. A procedure has been developed³ for describing the electric field, both within the radial-matching section and in the gap between the end wall and the vanes. The general quadrupolar symmetric potential expansion is used, and the coefficients are obtained numerically by a three-dimensional calculation using the program CHARGE-3D. This method allows an accurate representation of the electric field for arbitrary radial-matching-section geometries for later use in beam-dynamics simulations.

PARMTEQ SIMULATION USING MEASURED FIELD DISTRIBUTIONS

A method for using actual field measurements for PARMTEQ RFQ beam-dynamics simulations has been developed and has been applied to an RFQ.⁴ Measurements of the magnetic field in each of four quadrants are used to determine amplitudes of the four independent families of azimuthal cavity modes at each longitudinal position where measurements are obtained. In practice, only the quadrupole and two dipole modes give significant contributions. From a Fourier analysis of each amplitude as a function of longitudinal coordinate, a longitudinal cavity mode spectrum for each azimuthal symmetry is determined. Thus the measurements allow a characterization of the real cavity fields in terms of a Fourier series in the unperturbed eigenmodes.

A general multipole expansion of the potential can be written for the quadrupole and the two dipole modes. Although the dominant multipole term for the quadrupole cavity mode is the pure quadrupole term, other higher order multipoles will in general be present, depending on the pole-tip geometry. Likewise, the dipole cavity modes will in general give rise to higher order potential terms beyond the dominant dipole term.

The electrostatic program CHARGE-2D was used to determine the multipole terms in the potential arising from quadrupole and dipole cavity modes for an assumed pole-tip geometry consisting of four cylindrical conductors. The dominant potential terms are quadrupole and duodecupole for a quadrupole cavity mode, and dipole and sextupole for a dipole cavity mode. From these potential terms, the electric fields acting on the beam are obtained immediately. The beam-dynamics simulation program PARMTEQ has been modified to include these electric-field terms.

PARAMETER STUDY FOR A TDA RFQ

A parameter study for an RFQ for the technology demonstration accelerator (TDA) has been completed.⁵ The primary purpose of the study was to obtain early identification of an appropriate RFQ frequency or range of frequencies for the desired beam current and emittance. The studies were made for both H^- and D^- ions and for peak surface fields of twice the Kilpatrick limit. The frequencies under consideration were chosen based on power-tube availability. The RFQ design programs CURLI and RFQUIK were used to estimate the current limit, acceptance, phase advance, longitudinal capture efficiency, length, and power for each design. To determine output emittance, it is necessary to simulate the beam performance using PARMTEQ; consequently, a few of the designs were selected to be run in PARMTEQ to determine their output emittances.

A conclusion of the study was that the choice of RFQ frequency is confined to a rather narrow range by the simultaneous design constraints of high current and low-output emittance. The resulting frequencies were about 400 MHz for H^- and about 200 MHz for D^- .

REFERENCES

1. K. R. Crandall, "Effects of Vane-Tip Geometry on the Electric Fields in Radio-Frequency Quadrupole Linacs," Los Alamos National Laboratory report LA-9695-MS (April 1983).
2. K. R. Crandall, R. S. Mills, and T. P. Wangler, "Radio-Frequency Quadrupole Vane-Tip Geometries," Proc. 1983 Particle Accelerator Conf., Santa Fe, New Mexico, March 21-23, 1983, IEEE Trans. Nucl. Sci. 30, No. 4, 3554, (August 1983).
3. K. R. Crandall, "Electric Fields in the Radial Matching Section of an RFQ Linac," AT-1 memorandum AT-1:82-155, July 30, 1982.
4. K. R. Crandall and R. S. Mills, "PARMTEQ Simulations Using the Measured Field Distributions in the AT-2 RFQ," AT-1 memorandum AT-1:82-154, July 28, 1982.
5. T. P. Wangler, "Parameter Study for TDA RFQ," AT-1 memorandum AT-1:82-156, August 2, 1982.

ACCELERATOR INERTIAL FUSION

RFQ SYSTEMATICS FOR A SODIUM HTE ACCELERATOR

An initial study was made to determine some possible RFQ designs for use in a $^{23}\text{Na}^{+1}$ version of the high-temperature experiment (HTE) accelerator.¹ These designs were intended for use in later rf linac storage-ring design studies. RFQ designs were made at four different frequencies—6.25 MHz, 12.5 MHz, 25 MHz, and 50 MHz—and with a range of current limits. The beam performance for each design was simulated using PARMTEQ. The higher frequency designs tended to give smaller output emittances but were limited to less beam current. The high-transmission designs occurred at 50 MHz and yielded the highest brightness output beams, which frequently are of most interest for accelerator inertial fusion applications.

PHASE-SPACE CONSTRAINTS ON AN RF-LINAC STORAGE-RING DRIVER

The concept of an available dilution factor is useful for the characterization of heavy ion fusion accelerator systems or for any accelerator system with a limited-output phase-space volume. An available dilution factor corresponds to the amount by which phase-space density may be diluted by all processes between two specified points in an accelerator system, where the emittances are given. The restriction that this available dilution factor must not be less than 1 by Liouville's theorem and must, in practice, allow for all expected dilutions imposes a necessary design constraint.

We have concluded that it is important to specify available dilution factors separately in longitudinal phase space and in transverse phase space, rather than using only a single six-dimensional phase-space factor, to fully utilize the phase-space constraints. We have derived formulas for the available longitudinal and transverse dilution factors for an rf-linac/storage-ring system.² These formulas are expressed both relative to a point at the rf-linac exit and relative to the exit of the first stage (the RFQ) of the linac.

A SPIRAL-RESONATOR RFQ ACCELERATOR STRUCTURE

An RFQ structure operating at low frequency has been developed³ for possible use in accelerators for heavy ion fusion or tokamak plasma heating. The structure uses a series of shunt spiral inductors placed periodically along the electrodes of an electric quadrupole to achieve resonance at the desired

frequency. A 1.2-m-long model has been constructed for low-power testing. The model resonates near 12 MHz and has radial dimensions that are reduced by a factor of 15 compared to the commonly used four-vane resonator.

The increasing number of applications for high-current linear accelerators emphasizes the importance of the RFQ accelerating structure. The RFQ can accept a high-current dc beam from an ion source and focus, bunch, and accelerate the ions to several million electron volts per nucleon. For operation with very high current beams, often the RFQ must be designed to operate with such a low frequency that the resonator's transverse dimensions become unacceptably large. In this section we describe recent tests of a spiral resonator designed to provide low-frequency excitation to the four poles of an RFQ. The spiral resonator provides a substantial decrease in transverse dimensions compared to four-vane configurations that are commonly used.

RFQ accelerator techniques using frequencies in the range 80-450 MHz are now being applied in many projects. In addition, there are applications of RFQ accelerators operating with lower frequencies. These include the following:

- Heavy Ion Fusion
- Tokamak Plasma Heating
- Tritium and Fissile Material Production
- Directed-Energy Beam Research
- Advanced-Research Accelerators

Some of these applications may require the use of frequencies as low as 6 MHz, where the four-vane resonator would have a diameter of ~ 12 m. For RFQ use with frequencies below ~ 25 MHz, a marked reduction in resonator size must be obtained to reduce cost and to facilitate engineering design.

Requirements for high radial-brightness beams may limit the extent to which low frequencies can be applied. Different applications have greatly varying brightness requirements, some of which can be met through use of funneling techniques that are discussed later.

Analytical formulas have been developed to predict the beam current capability of linear accelerator systems. For the RFQ, these predictions have been confirmed in the POP experiment carried out at Los Alamos in 1980. The transverse current capacity is proportional to the wavelength squared, to the charge-to-mass ratio of the ion, and to the ion velocity. This means that low

frequencies are especially important to the production of high-current beams of low-velocity heavy ions.

The use of low-frequency RFQs is compatible with the method proposed to combine two bunched beams by funneling. In this scheme, two beams are combined by using a pulsed deflector to produce a single collinear beam with interlaced microstructure pulses. This beam then is further accelerated in a linac operating with twice the frequency. Multiple funneling stages and linacs of increasing frequency will progressively increase the radial brightness of the beam. This means that starting with low frequency does not commit the whole linac system to low-frequency operation. It also means that the lowest velocity structure, the RFQ, is at the lowest frequency, and thus the RFQ resonator size is a predominant consideration. The spiral-resonator RFQ is suitable for operation with a single beam or with an array having multiple beams that can be combined by the funneling technique.

The main objective was to test a spiral-resonator RFQ structure at low power to determine its rf characteristics. In addition, we wanted to solve some of the design problems that would be important to future high-power applications. An existing copper-plated tank 1.2 m long and 0.40 m i.d. was chosen to contain the spirals. Because only the rf properties were to be tested, the four RFQ poles were made from straight copper tubes 1.91 cm in diameter and 1.08 m long. Opposite poles were separated by 1.91 cm. The four poles were supported by four Archimedean spirals as shown in Fig. 1. At the center, each spiral was electrically connected to a diagonal pair of poles. Adjacent spirals were counterwound and were electrically connected to alternate pairs of RFQ poles. In each spiral plane, all four poles were mechanically supported. However, the insulators can be completely removed if desired; then the poles would be mechanically supported at every other spiral.

The spirals were constructed from stainless steel tubing having a 1.27-cm diam and a 0.165-cm wall thickness. A steel mandrel was mounted in a lathe chuck and was used to wind the spirals. After winding and before removal from the mandrel, the spirals were heat-treated to remove stresses. Electrical contact with the outer cylinder was made with a compressional fitting and a copper gasket. In future designs requiring cooling water, the flow can be inward to the center of a spiral, then along channels inside two poles, and finally can return outward through the second adjacent spirals.

Fig. 1.
Spiral-loaded low-frequency RFQ.

Radio-frequency tests determined the resonant frequency to be 11.7 MHz, and the quality factor to be 600. The next higher resonant mode is near 33 MHz. An equivalent four-vane resonator would have an ~ 6 -m diam; thus, the spiral model is a factor of 15 smaller. This reduction in size is obtained at the cost of increased power consumption; however, for low-duty-factor applications such as heavy ion fusion, this may be an acceptable method to obtain high-current beams.

REFERENCES

1. T. P. Wangler, "Preliminary Study of RFQ Parameter Options for a ^{23}Na HTE Accelerator," AT-1 memorandum AT-1:82-164, August 16, 1982.
2. T. P. Wangler, "Comments on Phase-Space Constraints on an RF Linac Storage Ring Heavy Ion Fusion Driver," AT-1 memorandum AT-1:82-254, December 13, 1982.
3. R. H. Stokes, J. M. Potter, F. J. Humphry, and P. L. Roybal, "A Spiral-Resonator Radio-Frequency Quadrupole Structure," Proc. 1983 Particle Accelerator Conf., Santa Fe, New Mexico, March 21-23, 1983, IEEE Trans. Nucl. Sci. 30, No. 4, 3554, (August 1983).

RADIO-FREQUENCY STRUCTURE DEVELOPMENT

FREE ELECTRON LASER

The buncher cavities for the free electron laser (FEL) were tuned. Measurements were made on a cold-model bridge coupler to determine the amount of field shift that could be obtained by asymmetrizing the bridge coupler. The field-shift range was found to be adequate for the requirements of the energy-recovery experiment. Modeling studies have verified the feasibility of the bridge-coupler scheme.

LAMPF II

The losses and tuning curves for several varieties of ferrite were measured at 50 MHz, using a quarter-wave coaxial-line resonator inside a solenoidal magnetic field.

PSR BUNCHER

Low-power tests of ferrites at 500 MHz were made for the Proton Storage Ring (PSR) buncher. A pair of dc magnets for testing the ferrites in a prototypical cavity were made. Work was begun on an aluminum prototype designed for cold tests to determine the coupling factors between the component cavities.

ACCELERATOR TEST STAND (ATS) RFQ

The ATS RFQ was placed into its rf manifold. The manifold was tuned to the correct frequency and stored-energy-distribution measurements were made. The fraction of stored energy in the manifold was less than desired, causing some difficulties in obtaining a good impedance match to the waveguide.

FMIT RFQ

For the Fusion Materials Irradiation Test (FMIT) facility, we have begun development of an electronic device to measure the RFQ vane gap using a linear photodiode array manufactured by Reticon Corporation of Sunnyvale, California.

RACETRACK MICROTRON

ACCELERATING STRUCTURE RESEARCH

Four different types of standing-wave, coupled-cavity, rf linear-accelerator structures have been investigated in a search for the best candidates for the racetrack microtron (RTM): disk-and-washer (DAW), annular-ring-coupled structure (ACS), on-axis-coupled structure (OCS), and side-coupled structure (SCS).

The SCS and OCS had already benefited from extensive development when the RTM project began. They are both in use at nuclear physics research facilities (LAMPF at Los Alamos and Institute für Kernphysik in Mainz, West Germany), and both enjoy widespread use in radiation therapy units (Varian Associates in California and Atomic Energy of Canada, Ltd., in Canada). Although these two structures are already very successful, the RTM application has performance requirements exceeding the demonstrated capabilities of existing units. These structures were reconsidered recently for the RTM application, and the results have been published.¹ Exhibits A through D summarize the salient features of the four structures.

During this reporting period, a third ACS model was constructed. This seven-cell model was built because two preceding models of ACS, having coupling constants of 13 and 12%, had very low shunt impedances caused by a quadrupole mode in the coupling cavity. This was particularly evident in the model with 13% coupling. The first two models had coupling cavities with different shapes, but the model with 12% coupling was not affected as severely by the quadrupole mode. We therefore tested this shape again but at 6% coupling. Only a small improvement in shunt impedance was achieved, so coupling was not the major problem and the quadrupole mode would have to be moved by other geometrical or mode-suppression techniques. This result eliminated this type of structure from our further consideration.

The SCS having a different fabrication procedure than that used at LAMPF appeared to be the best alternative. The FEL/LAMPF cell geometry directly scaled to the RTM frequency of 2380 MHz would give a predicted ZT^2 , including losses from surface finish, of 70 M Ω /m. This is unacceptably low, both because of length constraints imposed by available space at the National Bureau of Standards (NBS) and because of klystron power limitations. A study

EXHIBIT A: Side-Coupled Structure (SCS)

1. Sources of data
  - a. LAMPF at 800 MHz
  - b. FEL at 1300 MHz
  - c. Los Alamos 6-cell fully brazed RTM model
  - d. Los Alamos 43-cell RTM preaccelerator under construction
  - e. Commercial medical accelerators
2. Efficiency
$$ZT^2 = 80 \text{ M}\Omega/\text{m} \text{ (l.c above)}$$
3. Gradient

Peak surface fields will not exceed Kilpatrick limit should reach
>1.5 MeV/m
4. Coupling

5% (l.c above); requires shorter sections (~4 m)
5. Mode mixing

Accelerating mode well below all other modes; 2x modes avoided
6. Tuning during construction

Relatively straightforward
7. Tuning during operation

With pretuning and preset stop band open +200-300 kHz, expect no
field distribution shift at high power
8. Vacuum properties

Moderate conductance, pumping easily provided at every other coupling
cell
9. Ease of construction and durability

Two furnace-braze heats required per tank assembly
10. Preference for RTM: first (all aspects combined)

Weakest point: low coupling

EXHIBIT B: On-Axis-Coupled Structures (OCS)

1. Sources of data
  - a. CRNL power models at 3 GHz pulsed and 0.8 GHz cw
  - b. Mainz microtron at 2.45 GHz
  - c. Commercial medical accelerators
2. Efficiency

82 MΩ/m scaled from operational (1.a above and 10 below)
3. Gradient

1.8 MeV/m cw at 0.8 GHz
4. Coupling

5%; requires shorter sections (~4 m)
5. Mode mixing

None near the operating frequency
6. Tuning during fabrication

Poor access for tuning coupling cells
7. Tuning during operation
  - a. This structure operates well at the Mainz RTM
  - b. At full power, asymmetric heating of the double web might cause distortion and detuning
  - c. Potential for negative stop band opening at full power
8. Vacuum properties

Relatively poor conductance
9. Ease of construction and durability

The double water-cooled web would require two brazes per cell—flanges and iris would be easier

Webs must be thick enough to avoid grain growth leading to vacuum leaks; may compromise ZT^2
10. Preference for RTM: second

Weakness: low coupling and tuning during operation, reservations about achieving ZT^2 and accelerating gradient simultaneously because of web thickness required for adequate cooling and to avoid brazing problems

EXHIBIT C: Disk-and-Washer Structure (DAW)

1. Sources of data
  - a. PIGMI studies
  - b. Los Alamos 2.4-m, 2-stem RTM preinjector—high-power test
  - c. Continued 2- and 4-stem cold-cavity studies
  - d. USSR Meson Facility
  - e. Japanese work
2. Efficiency

79 MΩ/m measured (1.b above)
3. Gradient

1.7 MeV/m operational (1.b above)
4. Coupling

50% calculated (1.b above)
5. Mode mixing
  - a. TM_{11} and TM_{31} passbands cross operating frequency (1.b, 1.d, 1.e above)
  - b. Numerous modes at near 2x operating frequency
  - c. The 4-stem cold studies indicate TM_{11} stop band can be positioned around accelerating frequency, and no deflecting modes closer than 100 MHz to operating frequency (1.c above)
6. Tuning during fabrication

Relatively straightforward
7. Tuning during operation

No tilt in the field distribution was observed based on field measuring probes at each end of the tank
8. Vacuum properties

Excellent
9. Ease of construction and durability

Single-cell construction required numerous and difficult brazes
10. Preference for RTM: third

Weakest point: mode mixing

EXHIBIT D: Annular-Ring-Coupled Structure

1. Sources of data
Los Alamos two 7-cell, fully-brazed models
2. Efficiency
55 M Ω /m
3. Gradient
Untested: peak surface fields at design gradient not expected to exceed Kilpatrick limit—should reach 1.5 MeV/m
4. Coupling
12%
5. Mode mixing
Serious depression of Q caused by excitation of a coupling-cell quadrupole mode that is difficult to overcome because generically large circumference of coupling cell causes modes to lie near accelerating-cell modes
6. Tuning during fabrication
Limited experience
7. Tuning during operation
No experience
8. Vacuum properties
Relatively poor conductance
9. Ease of construction and durability
Only two braze heats required per tank section
10. Preference for RTM: fourth
Weakest point: mode mixing

Fig. 2.
The RTM structure cell assembly cross section.

of shunt impedance versus parameters made for LAMPF suggests that slight improvements to the shunt impedance could be made by decreasing the beam aperture and by sharpening the nose angle of the cavity (see Fig. 2).

The desired beam aperture size is 1 cm, which is 78% of the scaled LAMPF beam hole. This size, plus a reduction in nose angle from 30 to 10°, increased the theoretical shunt impedance by $\sim 18\%$ —99 M Ω /m. The peak surface field is still well below the Kilpatrick limit, and the actual measured shunt impedance in a seven-cell test structure for the RTM program is just over 80 M Ω /m. The reduction from theoretical is due entirely to decreased Q caused by surface-finish effects and the redistribution of current caused by the coupling slots. The measured value of ZT^2/Q , which is independent of cavity Q, was within 1% of the theoretical value of 5397 Ω /m.

A mechanical rf joint was developed to join sections of the side-coupled linac together. Basically, the joint uses a Conflat flange with an additional knife-edge to form a good electrical contact. Mechanical details are shown in Fig. 3. The measured Q of a single test cell using this mechanical joint is 83% of the measured Q of a similar, brazed cell. At the operating power level of 1750 W, this corresponds to 300-W dissipation in the joint, distributed over its 28.6-cm circumference. The estimated net joint resistance is 0.07 m Ω total or 2 m Ω ·cm.

A technique was developed for tuning accelerating and coupling half-cells, while still in place on a lathe, to within 300 kHz and 1 MHz, respectively. This tuning is achieved by machining to an accuracy of approximately ± 0.0003

Fig. 3.
The RTM flange design cross
section.

in. The frequency to which the cells are tuned has been estimated to correct for the effects of vacuum and temperature on the assembled structure and for the desired stop band.

The fabrication of the 2.7-m RTM preaccelerator side-coupled linac has been initiated. From measurements on the mode spectra (Fig. 4) of brazed assemblies, we estimate the rms tuning error to be ± 400 kHz with no additional tuning. This figure may be sufficiently accurate to obtain the desired field-distribution flatness of $\pm 3\%$. However, it probably will be necessary to tune the structure slightly after brazing to obtain the desired operating frequency and stop band.

The tuning of the accelerating cells will be accomplished by deforming the cell walls slightly at access points provided by drilling the structure at four locations per cell to reduced wall thickness. The accelerating cells can only be raised in frequency, whereas the coupling cells can be lowered by squeezing the gap or can be raised by spreading the gap with a wedge.

The small size of this structure permits a half-accelerating cell and a half-coupling cell to be made from a monolithic copper piece (Fig. 5). Two of these pieces and a stainless steel vacuum port are brazed together in a single heat. The resulting assembly has water channels in the septum and has a coupling cell with vacuum port. The braze alloy used for this braze is 65% Ag, 15%

Fig. 4.
Brillouin diagram showing the important
TM modes in the SCS.

ling factor β_2 is determined by the following relationship, where N_2 is the number of accelerating cells having quality factor Q_2 and β_1 is the coupling factor for a geometrically identical structure of N_1 accelerating cells having quality factor Q_1 :

$$\beta_2 = \beta_1 \frac{Q_2}{Q_1} \frac{N_1}{N_2}.$$

We assume that the fields are uniformly distributed in each case.

Pd, and 20% Cu and has a liquidus temperature of 1652°F. Good results have been obtained using this alloy at a brazing temperature of 1710° ± 10°F in making the copper-to-copper and copper-to-stainless steel braze. (Poor results manifested by porosity resulted at a temperature of 1760°F in copper-to-copper joints.) These assemblies are then brazed together with the 72% Ag, 28% Cu braze alloy having a liquidus temperature of 1436°F to form sections of the accelerator approximately a meter long. These sections will be flanged so that they can be bolted together to form a complete accelerator tank.

The six-cell brazed model was used to determine the approximate size of the coupling iris required for a full-length accelerator section. The coup-

Fig. 5.
The SCS cell design showing water-cooling channels.

For a coupling iris 28 mm long and 13 mm wide in a six-cell structure of $Q_u = 8000$, the waveguide coupling factor was 5.8. This same iris should yield a coupling factor of 1.0 in a 65-cell structure of $Q = 15\,000$. The detuning of the driven cell by this iris will be compensated for by further tuning the noses before the final brazing of this cell.

Using a least-squares fit to the ratio of the measured mode spectrum to the predicted mode spectrum, based on the coupled-circuit model, the parameters of the proposed microtron SCS were estimated. The measured mode spectrum was obtained from a brazed test section consisting of five accelerating cells terminated in half-cells at each end. Table I lists the estimated rf properties of the microtron side-coupled structure.

The SCRAM program was used to estimate the required tuning accuracy based on these parameters and the parameters listed in Table II.

TABLE I
CALCULATED PARAMETERS OF THE MICROTRON SCS

Accelerating-cell frequency	2389.6 ± 0.26 MHz
Coupling-cell frequency	2375.7 ± 0.23 MHz
Nearest neighbor coupling constant	0.0466 ± 0.008
Next-nearest-neighbor coupling constant	0.0036 ± 0.0003
Stop band	0.083 ± 0.35 MHz
Relative standard deviation of modes	54 ppm
Estimated standard deviation of cell frequencies	300 kHz

TABLE II
OTHER PARAMETERS OF THE MICROTRON SCS

Length	4.1 m
Number of accelerating cells	65
Accelerating-cell Q-factor	15 000
Coupling-cell Q-factor	7 500

For rf drive in the center of a 4.1-m-long section of SCS with parameters as given in Tables I and II, the estimated power-flow droop from the center to each end is 0.9%. The power flow phase shift is 3° per MHz of stop-band width. The tilt sensitivity (tilt produced by deliberately detuning the end cells equally and oppositely) is 8.5% per megahertz of stop band. The rms amplitude fluctuation is estimated to be 6% per megahertz rms tuning error per megahertz stop band, and the expected tilt magnitude is 19% per megahertz rms tuning error per megahertz stop band. Table III summarizes these properties for the case of a 0.3-MHz rms tuning error and a 0.5-MHz stop band.

The field errors listed in Table III are sufficiently small that reasonable tuning goals are 0.3-MHz rms cell tuning errors and less than 0.5-MHz stop band. To prevent the possibility of thermal runaway of the field distribution with increasing power level, the stop band should be deliberately set 0.2 to 0.3 MHz high. This is consistent with the requirements for field-distribution accuracy.

TABLE III
FIELD-AMPLITUDE DEVIATIONS WITH TUNING ERRORS
(0.3-MHz rms tuning error, 0.5-MHz stop band)

Power-flow droop	0.9%
Power-flow phase shift	1.5°
Tilt sensitivity	4.2%/MHz
The rms amplitude fluctuation	0.9%
Expected tilt magnitude	2.8%

CONTROL SYSTEM

During this half-year period, major efforts were made in (1) testing the rf secondary station with full-power rf operations, (2) development and construction of magnet power supply units with tertiary stations, (3) writing code for and testing of the resonance/temperature control system for structures under full power, (4) enhancing and expanding the secondary station interpreter code, and (5) arriving at a consensus between Los Alamos and NBS on final primary control-station configuration.

The rf secondary station has been operated, in conjunction with full-power tests of accelerating structures, without problems. Temperature sensors, frequency and power monitors, binary valve controllers and stepping-motor controllers all have been successfully operated from the secondary station. A resonance/temperature control system with the secondary station as the primary controller was designed and tested, with additional control algorithms implemented in an additional single-board computer (SBC) added to the station. This promises to provide adequate resonance control for the system, and vindicates again the distributed-bus structure of the control system by permitting additional SBCs without difficulties.

Design and construction of the magnet power supplies is proceeding according to schedule and within budget. Thirteen chassis, each with sixteen bipolar power supplies, currently are under construction and testing. As the units are received, they are tested with the secondary station linked to the tertiary magnet power supply station and under full load. We now have about half the required 200 units completed and tested.

The secondary station interpreter software has been enhanced by the addition of multiplication and division operators. We are now considering expanding this interpreter further and using it on the primary station as well as on the secondary stations.

After much discussion, the primary station has been configured with two joysticks as control elements, several color screens, and a green database screen.

REFERENCE

1. Radio-Frequency Structure Development for the Los Alamos/NBS Racetrack Microtron, Los Alamos National Laboratory document LA-UR-83-95, August, 1983.

CERN HIGH-ENERGY PHYSICS EXPERIMENT NA-12

Development of the fast-trigger system for the joint Los Alamos/CERN experiment NA-12 continues. During the last half of 1982, 513 eight-channel summing amplifiers were fabricated and inspected and were ready for testing in January 1983. In addition, 16 sixteen-channel fan-out boards were fabricated and tested. Design of the weighted summing amplifiers was begun, and prototypes of a fast inverter for negative-weight channels were tested.

HIGH-FLUX RADIOGRAPHIC LINAC STUDY

Radio skiagraphy and radio densitometry are powerful hydrodynamic diagnostic tools. Their applicability, however, is strongly dependent on the available bremsstrahlung flux. Typically, such a flux is produced by the deceleration of electrons in a high-Z target and is a function of the available beam power, the beam energy, and the pulse duration. A 1500-rad/pulse flux with a bremsstrahlung end-point energy of 50 MeV, for example, requires a beam power of roughly 12 000 MW for a 0.1- μ s pulse duration. The enormity of the required beam power for typical hydrodynamic applications has led us to study a stored-energy rf-linac approach to such applications. Even so, the allowable energy extracted from a stored-energy system is limited to $\sim 10\%$ of the total energy stored because of focusing requirements on emittance and energy spread. Nearly an order-of-magnitude increase in allowable percentage of energy extraction can, however, be attained by using a stagger-tuned cavity concept. Such a scheme permits an excessive energy time spread introduced in one accelerating cavity to be largely negated by an opposing spread in the succeeding cavity. Computer simulations have shown that, given a suitable injector, a 1500-rad/pulse, 50-MeV radiographic linac appears to be practical at a 400-MHz operating frequency and that a 150-rad/pulse, 50-MeV radiographic linac is feasible at 1300 MHz. The simulations followed the beam through the accelerator and focusing system to the target where the electron impact energy, the bremsstrahlung flux, the beam emittance, and the spot size were traced throughout the duration of the pulse. The simulations showed that the stated frequency/flux/energy parameters could be maintained while simultaneously restricting the spot diameter to 1 mm or less and preserving the angular flux distribution characterized by the energy.

The selection of realistic injector output parameters was critical to the validity of the study. This is particularly true of the emittance assignment. For an oxide cathode ($kT = 0.1$ eV and an emission density of 0.775 A/cm^2), the minimum achievable normalized emittance is $0.284\pi \sqrt{I} \text{ cm}\cdot\text{mrad}$ with I in amperes. Practically, however, the emittance can be expected to grow by, roughly, factor 10 because of the gun optics, the buncher, and the early stages of acceleration. The study, however, showed that all of the stated results could be maintained with a permissible emittance growth in the injector of factor 55.

PROTON STORAGE RING (PSR)

SUMMARY

Construction of the PSR tunnel and equipment building is proceeding on schedule. We expect to begin moving equipment into the ring tunnel in September 1983 as planned.

The design and procurement of equipment for PSR is on schedule also, and no serious obstacles are foreseen that would interfere with the scheduled start up of the PSR in the spring of 1985.

In the following sections we report on selected PSR activities that have had significant progress during this reporting period.

SWITCHYARD KICKER

The injection of H^- ions into the Line-0 transport line is controlled by the action of the switchyard kicker. This kicker is composed of a beamline magnet structure and an electronic driver assembly located in the LAMPF switchyard gallery. The magnet and driver are coupled through roughly 20 m of low power loss, low impedance, strip-line-type cable.

Final design of the magnet structure has been completed and includes two closely spaced, single-turn, window-frame-type magnets made from high-permeability ferrite material.

Both magnets, each 1 m long, are contained in individual vacuum vessels and are attached together as a single 2.5-m-long beamline element. The decision to use two magnets rather than a single device is based upon the available per-unit reduction in excitation current needed for each magnet and the per-unit reduction in electrical inductance. Combining both measures reduces driver design complexity and cost by permitting us to use efficient solid-state devices throughout the system's current-development circuits. The vertical and horizontal magnet apertures are 5 and 10 cm, respectively, and the developed peak-field per magnet will be about 500 G, giving a total beam deflection of $\sim 1.15^\circ$.

The specifications for rise time and flat-top regulation were established at 40 μs and 0.3% maximum, respectively, and the need for multiplexing operation (alternate kicker cycles having differing pulse widths) was established.

A model driver system composed of a 14-stage pulse-forming network (PFN) and a feedback-type current regulator was constructed and tested. The device

was attached to a prototype kicker magnet through a short strip line operated at 2000 A peak at 10 pps, with an ~ 50 - μ s rise time. Flat-top regulation was 0.5%. Measures to improve the peak current to 2400 A and regulation to 0.3% are under way, and methods to increase the duty factor to 24 pps are being designed.

The design of PFN line sections was completed, and a request for quotation for the entire grouping of PFN capacitors was initiated. A bridged-T-type section using a center-tapped inductor, a shunt capacitor attached to the tap, and resistive/capacitive damper bridging the network was chosen as the best line section. This configuration has inherent good impedance-matching properties, good section decoupling, and the energy storage in each section can be separately adjusted to compensate for coil resistance-related current droop.

A PFN charging concept using two different charging inductors, two control [silicon-controlled rectifiers (SCR)] switches, and a two-segment PFN also were tested for the first time. This circuit arrangement permitted alternate kicker pulses to exhibit different widths, thus successfully demonstrating the necessary multiplexing operations. The conceptual timing and control interface designs also have been completed. The overall kicker design has been frozen and is shown in the functional diagram of Fig. 6.

PULSED BEAM CHOPPER

The final design and prototype testing of a traveling-wave beam chopper have been completed recently. This chopper is required to provide properly structured negative-ion beam to the PSR and other LAMPF users. It must provide a 20-mrad kick with pulse rise time of < 5 ns for the 750-keV H^- ions in LAMPF's injector transport line. Variable pulse lengths from 15 ns to 750 μ s at repetition rates up to 16.7 MHz will be generated in synchronization with the PSR circulation frequency. Extensive parameter studies have led to an optimized design that combines good deflection efficiency and bandwidth with minimum effects from plate-to-plate coupling. Both positive and negative 600-V pulses, with lengths up to 1 ms and maximum 10% duty factor, have been generated to drive the deflectors.

Figure 7 shows what we call the coax-plate design, which uses flat plates on the structure's beam side soldered to and supported by short lengths of coaxial cable that connect adjacent plates across the back of the ground plane. The cables' lengths are adjusted to match pulse propagation to beam

Fig. 7.
Photograph of coax-plate structure.

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velocity. The plate width and spacing thus can be chosen to give the best compromise between efficiency and coupling. Because the coaxial cable provides most of the path length, deleterious effects from mismatch at the corners as well as coupling between turns on the structure's back are avoided. The plates' shape and spacing from the ground plane are adjusted empirically, providing 50- Ω impedance with minimum perturbation at the coaxial-cable transition. Individual plate replacement is accomplished easily without disturbing the rest of the structure.

The plates' thickness influences plate-to-plate coupling; therefore, we used 0.4-mm-thick spring steel for desirable stiffness, with copper-plating for better conductivity. We can thus maximize efficiency by making the plates 7.9 mm wide on a 10.2-mm center-to-center spacing for a 78% aspect ratio and a 94% calculated dc efficiency. The chopper's bandwidth, with an assumed spacing of 2.8 cm between deflecting structures, is $\sim$ 200 MHz. Two power amplifiers (positive output and negative output) with the following characteristics are required for driving the deflection structures.

Rise and fall times	<5 ns
Voltage output into 50 Ω	>600 V
Pulse width	<15 ns to >1 ms
Duty factor	10% maximum
Time jitter	<1 ns

An amplifier configuration using planar triodes and vertical metal-oxide semiconductor (VMOS) field-effect transistors (FETs) in a parallel cascode arrangement was chosen to meet these requirements. The cascode configuration takes advantage of the low output capacitance and high-voltage swing capability of the triode and wide-bandwidth transconductance of the rf VMOS FET.

Figure 8 shows a simplified diagram of the power-amplifier and deflector system. The amplifiers are operated on isolated decks so that the deflector base line is a ground potential. To produce the positive drive, the negative-tube output is inverted by a transmission-line transformer. To prevent excessive droop for a 1-ms pulse, the amplifier is isolated from ground by a low-capacitance isolation transformer and a fiber-optic signal link.

This development, including the POISSON calculation studies and laboratory measurements, has been documented.¹ Final construction of the two power amplifiers, the deflecting structures, and the vacuum box is scheduled for completion early in 1984.

Fig. 8.
Power amplifier simplified block diagram.

PSR ORBIT DISTORTION SYSTEM

A system of pulsed air-core magnets ("bump" magnets) will be used in the PSR to provide vertical distortion of the closed orbit during injection. The system sweeps the ring closed orbit over the injection stripper foil and thus permits control of the rate at which particles are injected into a given region of stored-beam phase space. Additionally, interaction of the stored beam with the foil is minimized by suitably shaping the current pulse applied to the magnets. The general scheme and rationale for the system have been extensively discussed.^{2,3}

Orbit Bump Magnets

Figure 9 shows the position of the bump magnets centered around the PSR injection section. The placements are a compromise between optimum positioning, magnet driver capabilities, and component space conflicts. The two magnets upstream of the foil straddle the second extraction septum and act in concert to deflect the beam orbit upward by ~ 2 mrad. This kick effectively

Fig. 9.

A plan view of the PSR injection section showing the bump magnets' position.

determines beam position on the foil. Two magnets are necessary to provide the required deflection without excessive strain on driver design. A third magnet, just upstream of the foil, adjusts the beam slope, thus completing specification of vertical phase space at the foil. Similarly, the magnets downstream of the foil return beam to the closed orbit.

The injected beam from LAMPF, which has an emittance much less than that of the stored beam, is focused on the horizontal-edged stripper at a constant vertical displacement (relative to the ring closed orbit) equal to the extreme coordinates of the stored beam. At the start of injection, the bump system deflects the equilibrium orbit to the injected beam coordinates. As injection proceeds, the deflection decreases at a rate appropriate to production of the desired transverse beam-density distribution. Because accumulation occurs at the beam surface, interaction with the foil is minimized. After injection is complete, the orbit perturbation is zero and the beam no longer interacts with the foil. A ray trace of an extreme orbit deformation for matching into a stored beam with emittance of 2π cm·mrad is shown in Fig. 10.

Fig. 10.
Ray trace of equilibrium orbit deflection in vertical plane.
Ring sections viewed are the same as Fig. 1.

Magnet Design

A sketch of the proposed single-turn air-core magnet configuration is shown in Fig. 11. The inner surface of the copper electrodes is concave to provide control of field homogeneity. Calculations and experiments on a prototype model have been done with dimensions as given in the figure. These show that the field produced in the magnet for a given current is a strong function of the driving frequency because of the currents induced in the vacuum-chamber walls by the time-varying magnetic fields and by the redistribution of current in conducting surfaces as the frequency is changed. The field at the magnet center decreases with frequency to an asymptotic value. The maximum rate of decrease occurs at about the frequency for which the skin depth equals the chamber-wall thickness. This behavior causes distortion of the field's pulse shape and amplitude from that observed if the magnet were linear. Figure 12 shows this behavior for a pulse similar to one we might use in injection programming for the short-pulse mode. Injection occurs at $t = 0$ on the plot, and the pulse rise time is made short to decrease the required duty factor. The field amplitude is decreased to 60% of the required value, and the pulse is

Fig. 11.

Sketch of single-turn bump magnet. A prototype magnet was built with $R = 7.2$ cm, $L = 48$ cm, $d = 7.6$ cm, $w = 10.5$ cm and $t = 0.2$ cm. The chamber is stainless steel and the electrodes are copper, 1 cm thick at the edges.

Fig. 12.

Relative fields versus time for an input-current waveform proportional to the upper curve that shows the linear response. The lower curve shows the response of the prototype magnet.

severely distorted. To avoid a large additional effort in magnet design, the amplitude distortion must be remedied by increasing the vacuum-chamber radius to ~ 13 cm so that wall-induction effects will be sufficiently small.

Our analysis also has specified the magnet impedance as a function of frequency, an important parameter for modulator design.

Modulator Design

A simplified schematic of the proposed modulator circuit is shown in Fig. 13. The circuit uses solid-state devices instead of the usual high-voltage tube technology, common for similar fast-pulse applications, resulting in a small and inexpensive package. This is possible through judicious design, use of state-of-the-art semiconductors, and maintenance of low inductance in the magnet design. The circuit consists of a linear amplifier that drives a high-power VMOS p-channel transistor proportionately to a programmed input.

Fig. 13.

Simplified schematic for the vertical bump-magnet driver showing matched transmission line and constant-impedance-load network.

This output will be "mirrored" (to provide a linear output without high-current feedback) by a set of n-channel devices that includes the magnet load and is adjusted to present a constant impedance to the drive circuit.

Project Status

The magnet design is complete, and final construction will begin upon completion of engineering drawings. Space has been allocated in the ring for magnet placement. Operation of the driver circuit has been demonstrated to 500 A; final construction of the full-power units (2500 A) is proceeding.

For initial ring turn-on, three magnets and drivers will be installed. This will suffice to remove the beam from the foil after completion of injection but will provide no phase-space manipulation. For high-current studies, the full set of six magnets will be used.

EXTRACTION KICKER PROGRESS

All efforts from July to December of 1982 primarily were in support of the short-bunch modulator. Primary achievements are listed in chronological order.

- Final design and construction of five high-power drivers for triggering the output switch tube in each modulator. These units are triggered by optic links and provide 300-ns-wide, 3000-V pulses across $25\ \Omega$ at any repetition rate from 1 to 1000 pps. Overall jitter is 200 ps peak to peak for 10 000 pulses at 720 pps.
- Various modes of triggering the HY-5333 thyratron were investigated using the previously mentioned driver. Simultaneously triggering both the control and auxiliary grids without bias proved to be most advantageous.
- The Q circuit, responsible for regulating the output pulse amplitude of the modulators, was installed and tested. Output regulation was measured at less than 0.05% deviation.
- CAMAC hardware was acquired, and a program was written and developed that measures the output pulse jitter of the short-pulse modulator. The modulator is run under computer control and is shut down when either output pulse jitter or drift becomes

excessive. This mode of operation is necessary to prevent fatal thyatron damage when internal tube arcing occurs.

- Several fiber-optic links were tested as candidates for triggering the modulators with low jitter. The most satisfactory of those tested was a Merit Inc. Model MDL 259-20, which had 400 ps of jitter, at a cost of about \$2300 each. In a related area, an RFQ for the fiber-optic data channels for each of four modulators was released and vendors were selected. The total acquisition cost was about \$30 000.
- A device was designed and constructed to accurately measure the short-pulse modulator output pulses. This device uses current transformers to measure the current flowing in the shields of the output cables.
- New short-pulse modulator Blumlein circuits were constructed and installed to take advantage of new low-inductance cable junctions. This modification also makes output cable installation easier.
- The short-pulse modulator has run successfully at 40 kV at 720 pps for over 500 h using a single HY-5333 thyatron. This test demonstrates the feasibility of using a thyatron at PSR-required voltage and repetition rate. The HY-5333 was removed to test an improved version, the HY-5353.

REFERENCES

1. J. S. Lunsford and R. A. Hardekopf "Pulsed Beam Chopper for the PSR at LAMPF," Proc. 1983 Particle Accelerator Conf., Santa Fe, New Mexico, March 21-23, IEEE Trans. Nucl. Sci., 30, No. 4, 2830, (August 1983).
2. D. W. Hudgings and A. J. Jason, "Injection System for the Proton Storage Ring at LASL," Proc. 11th Int. Conf. on High Energy Accelerators, CERN, Geneva, July 7-11, 1980, Experimentia: Supplement 40, p. 277, 1981.
3. A. J. Jason, E. F. Higgins, A. R. Koelle, "The Los Alamos Proton Storage Ring Injection Deflector System," Proc. 1983 Particle Accelerator Conf., Santa Fe, New Mexico March 21-23, IEEE Trans. Nucl. Sci., 30, No. 4, 2830, (August 1983).

FREE ELECTRON LASER

For the oscillator experiment, this period mostly was one of component completion and system assembly. Work on various projects is discussed below.

INJECTOR

Two electron guns were assembled and tested. Problems with their electrical and thermal properties finally were solved by using oil as a thermal transfer medium as well as the major insulator. The gun pulser was tested and operated as expected. The small solenoids were calibrated and aligned with the beamline.

With the exception of the large-bore solenoids, all components for the subharmonic triple-buncher system are completed. The two subharmonic bunchers (108.3 MHz) and the fundamental buncher (1300 MHz) were machined, tuned, and brazed. The resonant frequencies and quality factors were close to those as calculated by SUPERFISH. The support table and brackets for the bunchers and solenoids were completed, and all vacuum components were received. A variable aperture ladder for beam attenuation and two sets of steering coils were fabricated.

Three broadband wall current monitors were fabricated to measure bunching and beam transmission in the injector.

Two of the seven solenoids were positioned by finding the loci of zero radial magnetic field using a transverse Hall probe.

RADIO FREQUENCY

During the previous reporting period, the capacitor bank was completed. Most other elements necessary to operate the first klystron were close enough to completion to be usable, but were not quite up to full performance requirements.

The capacitor-bank dump system was tested to its full required voltage of 120 kV. The klystron modulator was improved so that a 100- μ s flat-top rf pulse could be obtained without exceeding a 125- μ s video-current pulse through the klystron. All three of the L-3707 klystrons were tested to 3.7 MW peak, unsaturated, with 100- μ s rf pulses at 10 pps. Design of the waveguide

system was completed and installation was begun. Fabrication of the first phase-and-amplitude control system was 80% complete with initial testing to begin early in 1983.

ACCELERATOR

The accelerator consists of two accelerating tanks providing a 21-MeV beam energy. Sections of the previous accelerator, used in the FEL amplifier experiment, have been combined with new copper segments to construct the two tanks. The first tank has a tapered- β input section and consists of 13 main accelerating cells. The second tank consists of 15 main cells, all with $\beta = 1$. Each tank will operate in the steady-state mode with an ~ 7 -MeV/m energy gradient.

Two coupling loops have been installed in each accelerating tank to provide feedback signals for monitoring the cavity fields and for rf phase and amplitude control. Control of the relative rf phase between the accelerator tanks and the bunchers is essential for proper accelerator operation and to minimize single-bunch beam loading.

Final assembly of the accelerating tanks is complete. All joints, including those at the waveguide window, are vacuum tight. Final bead-pull data indicate a maximum variation of a few per cent for peak cavity fields within each tank. Assembly of the waveguide and water system for the second tank is in progress.

ELECTRON-BEAM DIAGNOSTICS

The spectrometer was modified, and two time-gated, intensified video cameras were mounted to view the fluorescent screen in the spectrometer's image plane. Their system was checked and calibrated.

The concept of the slow and fast deflectors was broadened so that they can be used to analyze many features of the electron beam. Their designs were completed and construction began.

OPTICAL CAVITY

Samples of the resonator mirrors are in place. Their remote alignment and spacing equipment has been tested. Several different designs for sharp, cutoff, optical filters are being considered. These may be important for suppressing growth of sidebands.

DATA RECORDING

A complex system to record the data from the e-beam and optical diagnostic equipment is being collected. It includes a video tape recorder and a multitude of TV cameras and other electronics viewing the e-beam screen, various oscilloscopes, etc. This flexible system will freeze transient events, gather all the data from a given shot, and save all these data for later retrieval and analysis.

ENGINEERING SUPPORT

In September, significant mechanical, electrical, and rf-system design support was mobilized for the FEL oscillator and energy-recovery experiments. Our efforts have ranged widely over beamline and support systems. Among the designs completed and installed in late 1982 were a beamstop, spectrometer modifications, electron gun, ladder aperture assembly, waveguide and coaxial installation, and miscellaneous facility improvements. Designs were completed and fabrication is now in progress on a slow deflector, a fast-deflector cavity, and a shield system for the bending magnets. All of these efforts have been on the oscillator-experiment hardware.

FUSION MATERIALS IRRADIATION TEST FACILITY

STATUS

A Senior Advisory Panel (SAP) was formed to evaluate the desirability of international participation in the funding for the FMIT Facility. The SAP reports to the Fusion Energy Office of the International Energy Agency; the first meeting of the SAP occurred in December. In this interim period, the United States is continuing to fund the accelerator program at Los Alamos National Laboratory and the lithium target and experimental-system programs at the Hanford Engineering and Development Laboratory (HEDL), Richland, Washington.

At Los Alamos, the emphasis remains on installation and initial start up of the 2-MeV accelerator. All major components were received or are in an advanced state of procurement. The operation of the accelerator now is scheduled to commence in late May 1983. The formal report of the Test Plan Committee was distributed to relevant personnel for comment or preliminary approval.

Characterization of the injector low-energy beam-transport (LEBT) system, development of the rf-power amplifier system, and evaluation of the design for many components of the high-energy beam-transport (HEBT) system and RFQ peripherals has continued. Assembly of the 15 drift tubes required for the Alvarez linac in the 5-MeV accelerator has been completed. The drift tubes need only to be copper-plated before they are ready for use.

ACCELERATOR

Injector

The most significant progress achieved in FMIT-injector operations during the last half of 1982 resulted from a redesign of the extraction electrodes. A computer code was used in an attempt to optimize electrode configurations, and the resulting electrode shapes were used in another code to simulate the results. Several electrode configurations were examined, and the final configuration theoretically reduced the emittance by a factor of 4. This electrode configuration then was machined, using the numerically controlled Mazak mill, to accurately reproduce the theoretical shapes. With the new electrodes installed, the measured beam emittance improved by nearly a factor of 3. The new configuration also significantly improved injector operations,

in general, by reducing the sensitivity to fluctuations in extraction voltage and ion-source parameters.

We found that commercially sintered tungsten filaments improved ion-source operations. The lifetime of the previously used wire-mesh, oxide-coated filaments was only about 30 h. The sintered tungsten filaments have lasted more than 150 h, even after twice being exposed to air. We expect that with continuous operation, the FMIT lifetime requirements (350 h) can be achieved easily. The fraction of the beam contained in the hydrogen ion species also increased from ~60 to over 70%, indicating substantially fewer heavy ion contaminants in the arc plasma.

Some problems connected with ion-source operation also were solved during this reporting period. With four rows of magnets around it, the ion source operated in an unstable region with respect to arc voltage. In effect, the ion source behaved like a relaxation oscillator with a 2- to 10- min period. The arc voltage would increase slowly until, evidently, the plasma changed modes; then, the arc voltage would drop suddenly and repeat the procedure. Whenever the arc voltage changed suddenly, the surge current would trip off the high-voltage power supply. This problem was solved by reducing the number of magnet rows, first to two and finally to one. With two rows of magnets, the H^+ species fraction was enhanced over H_2^+ and H_3^+ . With one row of magnets, the H_2^+ current is enhanced; hence, it may be possible to run either H_2^+ or D^+ beam simply by adding or removing the second row of magnets on the ion source.

Remote operation of the injector LEBT was demonstrated during this period. Full control of all parameters for the ion source and focusing magnets was achieved. Daily operations, however, still are done locally to facilitate computer-program development on the primary computer.

Continuing problems with the high-voltage power supply (HVPS) have somewhat hampered injector operations. An inductor was constructed to try to isolate the reactive load of the ion source from the resistive feedback circuit of the high-voltage power supply. Preliminary results are very encouraging, and evaluation of the benefits of this system is continuing.

Beam-current control by gas mixing gave promising results during preliminary testing. The gas-control chassis of the injector was replaced with a dual-channel commercial unit, and the performance has been satisfactory. We can achieve approximately a factor of 3 reduction in beam current (both H_2^+ and H^+) simply by increasing the hydrogen flow. However, we have observed some

problems with arc stability when mixing in argon. To reduce the sensitivity of the arc plasma to the injection of the control gas, the gas was changed from argon (with three times the hydrogen-ionization cross section) to neon (with only one-fourth the hydrogen-ionization cross section). Evaluation of the gas-mixing method of beam-current control is continuing.

The RFQ Linac

All contracts for the major RFQ components were out by mid-1982; fabrication on the vanes, core tank, and manifold tank progressed smoothly into early 1983. Vane-tip machining was completed in November, and acceptance inspections began on the core and manifold tanks in December.

Assembly of the RFQ began, following cleanup and vacuum testing of the various components. A small amount of repair work had to be done. The vanes were installed easily, and the rf seal wires between the vane bases and the core tank were installed successfully. The vane bellows fractured during assembly but will be repaired after rf tuning is completed.

Beam Diagnostics

The noninterceptive, beam-distribution measurement system was applied to a single TV camera view through a relatively wide view port. Three longitudinally separated lines from this single view were used to estimate beam emittance. A new computer code was written to compress the inordinately large amount of data in a TV frame to a set of four beam profiles, thus saving memory on the Winchester disk and facilitating archiving of raw data. Another new code provides rapid output of beam widths.

The alternative system of imagescope, microchannel plate (MCP), image intensifier, and photodiode array was installed on the beamline. The beam profiles are imaged onto the optical fibers of the imagescope by an input lens that occupies less than 3 cm of beamline. The images are transported through the MCP intensifier to the photodiode arrays. The arrays are read out through an analog-to-digital converter (ADC), and the digitized profiles are transferred to the CAMAC system over an optical fiber. Both the digitizing electronics and the CAMAC input module are in a wire-wrapped version. A digital-to-analog converter (DAC) was installed in the CAMAC module to provide real-time beam profiles as a scope display for the operator. This feature has proved to be a valuable tuning aid. The digital profiles are used for the

tomographic reconstructions of beam distributions in a fashion identical to that of the TV camera data. The imagescope-to-photodiode system is expected to be less expensive, to be more flexible in its application, and to provide better quality data.

The time-loop test stand was fabricated, assembled, and tested. Its performance met the design criteria excellently: it must have greater than 1-GHz bandwidth with a nearly flat spectrum; it must have a voltage standing-wave ratio (VSWR) of 1.6; it must be mechanically functional. Preliminary tests of the capacitive probes have shown them to respond as predicted. The 80-MHz current transformer was received, and check-out was completed.

The rf System

The first high-power rf system was received from Continental Electronics, Dallas, Texas and installed in the dummy-load test stand for acceptance testing. After initial testing, the final amplifier was disassembled to replace the tube, an 8973, that had been behaving erratically at full power. We discovered that the output directional coupler was faulty in both coupling calibration and directivity. These errors had caused us to improperly dope the sodium nitrite solution in the load, so that instead of having a load VSWR of 1.4, it was actually closer to a VSWR of 3.0. The tube and amplifier were not designed to run at full power into a VSWR of 3; therefore, in retrospect, the observed erratic behavior was not surprising. In subsequent tests, the system easily came up to 600 kW.

Dummy-load testing of this high-power rf system was concluded because of problems with the dummy load. We had operated at 600 kW into a 1.4 VSWR with both V_{MAX} and V_{MIN} at the tube. The amplifier also had operated into an open-circuit line at 250 kW, pulsed, with no problems. The system then was moved from the test stand and connected to the linac tank with the dummy drift tube (DDT) for resonant load tests.

The rf conditioning of the DDT tank was completed within 18 h. The rf system was run at the full-peak output power of 600 kW with a 1-ms pulse length and a pulse repetition frequency of 50/s resulting in a 5% duty factor, the maximum for which the DDT was designed.

The rf system on the linac tank was run routinely at intermediate power levels while testing the feedback control systems. The frequency control

system was modified and adjusted, and is now performing quite well. The frequency control system is able to track the tank frequency in the variable frequency mode until the crystal frequency is reached, at which time the tank frequency is held to the crystal frequency by slug-tuner action. The phase and amplitude feedback control systems also operated satisfactorily.

Acceptance testing of high-power rf System No. 5 has been successfully completed at Continental. Shipments of high-power systems to HEDL should begin in late January or February. Two different EIMAC 8973 FPA tubes were installed under test to determine if the system would behave stably when a tube is replaced. Results were satisfactory. All the modifications implemented on System No. 5, particularly in the screen cavity, are being retrofitted on the units at Los Alamos.

Facility Control System

The operation of the instrumentation and control (I&C) system described in a previous report¹ has been enhanced by adding a new node to control magnets and a system to survey all measurement channels. The system reports to the operators any conditions outside preset limits.

The magnet-control node is a subsystem consisting of an LSI-11/23 microcomputer with CAMAC input/output modules that communicate with various sensors and dc power supplies. This subsystem controls the currents in all the magnets that focus and steer the accelerator beam and does so in response to commands from the main operator console in the control room.

The alarm-reporting system consists of a program that runs independently in each node, examining each data channel according to a schedule contained in that node's database. Each reading is compared to limits contained in the database and is reported only if the limits are exceeded. If an alarm limit is exceeded, appropriate information appears in red on a color monitor in the console, and an audio annunciator calls the operator's attention to new alarm data.

Unreliable operation of the microcomputer systems that are in the severe electrical environment of the injector was a problem that has been solved by isolating the power supply and improving the shielding and grounding. In one case it was necessary to move the microcomputer to a different cabinet, away from the wires bringing signals to the CAMAC modules.

Drift-Tube Linac

A conceptual design review of the FMIT drift-tube linac (DTL) tank's end wall, an all-copper construction, was held in November. The detailed design and analysis of the linac support stand were completed, and a review of the proposed changes to the tank drawings was conducted. The drafting section completed a set of prints with revisions marked to describe the requested engineering changes. A work package was prepared for completing the FMIT tank design based on these changes.

Besides serving as a resonant load for the high-power rf system, the DTL/DDT assembly has provided a test bed for the slug tuner and rf drive loops. Both of these components have been operated at full peak-power levels and have not revealed any design flaws, thus allowing procurement of the two RFQ drive loops to proceed with confidence. The additional three slug tuners required for the RFQ manifold tank were received also and were performance-tested satisfactorily. Thus, all essential peripheral rf components are ready for final assembly of the RFQ.

During the rf testing of the DTL/DDT at high power, some ion-pump failures occurred. One suspected reason was excessive rf leakage into the ion pumps down the below-cutoff vacuum ports. Since then, a pickup loop was installed in the throat of an ion pump, and rf power was detected there. The level of power has not yet been determined. The cutoff power level is calculated to be attenuated by 31 dB. If it is higher than this, rf grills are available for a test to determine if higher attenuation can be achieved.

High-Energy Beam Test for HEBT

Design of the HEBT to service both the 2- and 5-MeV prototypes was completed late in 1982, and all components were placed under procurement. The HEBT is being completely assembled and vacuum tested.

The three 25-cm quadrupoles in the HEBT were tested and shimmed using the CERN shimming technique. Excellent results were obtained with sextupole and duodecapole field harmonics reduced to below 0.1% of the quadrupole field.

The beamstop plates were received from the fabricator and were successfully brazed. All are vacuum tight and have been installed on the support framework. The large beamstop vacuum chamber (3.6 m^3) also was received from the manufacturer and vacuum tested satisfactorily.

FMIT-Related Research

The technical development section has obtained some excellent results for radiation-hardened magnets for FMIT. A glass-coated field-coil design was perfected for the drift-tube quadrupoles beyond 10 MeV. This design uses a refractory cement bonding agent to pot the coil. A sample unit was fabricated using the same coil design as the A-type FMIT field coils. It was then tested at 1000 A for thermal shock. No cracking of the vitreous sheath or the cement bond was detected.

Another research program developed a radiation-hardened field coil for the FMIT HEBT quadrupoles located 2 m upstream of the lithium target. These magnets receive over 10^{11} n/s·cm² at elevated energies and must be not only totally inorganic, but must even be protected from free-oxygen dissociation of the water. A lead-impregnated test coil using mineral-insulated solid-core conductors and indirect cooling in stainless tubing was built and tested. Remarkably good results were obtained at 2.5 times the FMIT current rating. The coil demonstrated that it can tolerate current densities of over 2000 A/cm² at a conductor temperature of 305°C without short-term failure.

A third program undertaken was the development of an experimental model of the graphite-plated beamstop required for the 5-MeV prototype and for FMIT. A full-power test model has been designed to fit into the HEBT where it can receive 500-W/cm² heating from the 2-MeV beam. Graphite chips will be glued on, using various refractory cements to test compatibility with FMIT needs.

During this period, one patent (U.S. Patent #4 350 921) was issued to personnel in the Systems Integration Group in AT Division and another is pending. The issued patent deals with the drift-tube suspension for high-intensity linacs; the pending patent is for the vitreous enamel process for radiation hardening the magnet field coils.

REFERENCE

1. R. A. Jameson, Compiler, "Accelerator Technology Program, January-June 1982," Los Alamos National Laboratory report LA-9914-SR (December 1983).

KLYSTRON DEVELOPMENT PROJECT

The ring-model klystron code was improved and tested in the reporting period. The iterative, self-consistent gap-field calculations were implemented, and the beam harmonic currents and induced currents were correctly calculated. Several test runs based on the LAMPF klystrons were made, with and without space charge. These first calculations of the complete five-cavity klystron produced efficiencies between 40 and 50%, very close to the experimental values. However, many more calculations are required to determine the parametric dependence on the input variables.

Two major new aspects of the code have been addressed. The trajectories with space charge initially had a nonphysical, radial motion that depended on the subdivision of the beam into rings. Several methods of integrating over the finite dimensions of each ring were considered, and a satisfactory solution has been found.

The code must treat the case where one wavelength of electrons is distributed in several cavities at the same instant. This is only a bookkeeping problem, but it is rather difficult and is a well-known problem with time-stepping, particle-tracking codes. This aspect is also now in hand.

Several methods of quickly finding the self-consistent, steady-state solution to the equation are under consideration. The code usually takes 6 to 10 interactions on each gap before a self-consistent solution is found.

GYROCON PROJECT

At the beginning of the reporting period, the prototype gyrocon was producing 50-kW output pulses 50 μ s long at 446 MHz with a 1-Hz repetition rate. After several weeks of operation, the output power was increased to 100 kW with 5.3 A and 86 kV of input power. The electron gun was performing well, and the modulating anode circuit was modified to produce 8 A, the design current. This change produced 150-kW pulses and an overall efficiency of 23%.

Several more weeks of operation yielded no increase in output power. Tuners were placed in the output waveguides to vary the loaded Q, and thereby to vary the rf voltage in the output cavity. The expectation was that if the cavity could be conditioned to a higher voltage, more output power could be produced when the loaded Q was optimized again. However, the maximum output power remained at 150 kW, and the optimum loaded Q was half the unloaded Q of the output cavity. In the final experiment, the output cavity was disassembled and coated with a thin layer of titanium. The gyrocon was reassembled and tested, but again 150 kW was the maximum output power. The pulse length was increased to 400 μ s, and the output remained constant.

The experiments so far have definitely proved the feasibility of the gyrocon's operating principle. The output power is quite sensitive to the phase of the two drive signals, the output-cavity tuning, and the magnets' settings. The direction of the beam's spiral also is important, as has been predicted by the analysis code. The reasons for the difference between the actual performance and the predictions of the analysis code remain unknown. Most likely, the difference is caused by the fringe fields that extend through the output-cavity gap. The output-cavity gap is 8 cm wide in a cavity that also is 8 cm wide. The fringe fields extend rather far, both into the bender region and into the collector region, whereas the code assumes that the cavity fields end abruptly at the inner and outer radii of the output cavity. The true transit time of the electrons in the output fields may be substantially larger than the time used in the code, and this may be the reason for the major discrepancy between the theory and experiment. Some analysis of the fringing problem has been done, but information resulting from the analysis has not yet been incorporated into the design code. A method of attaching grids to the apertures on the output cavity has been designed, and a grid between the output cavity and the collector shall be tried in the future.

ACCELERATOR THEORY AND SIMULATION

The Accelerator Theory and Simulation Group, AT-6, was formed in March, 1982. The charter of the group is to provide theoretical support for the various projects of AT Division, which includes not only analytical support but support in the use of computer codes used in accelerator theory and design.

The range of topics treated by AT-6 is illustrated by the following that serves as a list of entries for the brief description of progress items.

- Cumulative Beam-Breakup Instability
- A Fast, 3D, Particle-Tracing Code
- Moment-Method Description of Charged Particle-Beam Behavior
- Equipartitioning
- Ion Arcing in the RFQ
- Effects of Errors on RFQ Performance
- Correcting Closed-Orbit Distortions in PSR
- Stability of the Short-Bunch Operating Mode in PSR
- Longitudinal Space-Charge Effects in LAMPF II
- Solenoid Optimization Code
- POISSON Group Codes and URMEI

CUMULATIVE BEAM-BREAKUP INSTABILITY

This instability is a result of a linac beam interacting with TM modes of the accelerating structure; such modes have $\cos \phi$ or $\sin \phi$ dependence (for example, the TM_{110} mode of a pillbox cavity). These modes have a uniform magnetic field near the symmetry axis and therefore deflect the beam as a whole. The analysis of this instability gives rise to two coupled difference equations that include the effects of focusing and rf structure. These equations have been solved exactly, analytically.

A FAST, 3D, PARTICLE-TRACING CODE

To study effects of parameter variation in RFQs in doing RFQ designs and studying effects of errors, a fast, 3D, particle-tracing simulation code was developed. In this code, space-charge forces are calculated by fitting the

particle distribution at each time step to an ellipsoid with a parabolic charge-density profile by comparing the particle moments with the known properties of the parabolic ellipsoid. Space-charge forces through cubic order then are computed for the corresponding parabolic ellipsoid. The required 3D integrals are approximated by using an expansion about a sphere. This expansion has been computed symbolically with the MACSYMA system.

MOMENT-METHOD DESCRIPTION OF CHARGED PARTICLE-BEAM BEHAVIOR

The popular method of describing charged particle beams by using an envelope equation results from taking second moments of the beam distribution function and making some simplifying assumptions about this function. In the work reported here, the fundamental equations describing the time evolution of the 3D moments of charged particle beams were derived, and the relation between the moments and the space-charge coefficients was obtained. The lowest order (second) moment equations were implemented in a code, and the theoretical details for a fourth-order code were derived. Preliminary work was begun on using the MACSYMA system to do the symbolic manipulation required in generating FORTRAN code that simulates linear accelerators by the moment method. We are using this approach because it is not practical to work out the equations by hand to higher than fourth order, although higher order moment-evolution equations could be integrated numerically to describe accurately the time evolution of the phase-space distribution.

EQUIPARTITIONING

An attempt to discover collective equipartitioning instabilities in charged particle beams in a fluid model failed. We discovered that fluid models do not even allow nonequipartitioned equilibria, thus casting doubt on a previous theory based on the Kapchinskii-Vladimirskii distribution function.

ION ARCING IN THE RFQ

The observation of beam-induced breakdown in the RFQ led to investigations of electron multipactoring trajectories. When the electron trajectories were found to be highly unstable, a theory of ion arcing was formulated. The ion-arcing theory was found to be capable of explaining all the observations.

EFFECTS OF ERRORS ON RFQ PERFORMANCE

The effects of machine errors on RFQ performance were studied using the fast, 3D, particle-tracing code, described above, whenever simulations were required. Both random and slowly varying errors were studied. A match does not exist for a structure with random errors, which means emittance growth will occur for any choice of initial phase-space distribution. Slowly varying errors are harmful because they can reduce acceptance, even though they will maintain a match for an initially matched beam (up to the point of particle loss).

We found that RFQs are too short for random error effects to be described by a diffusion equation. This means we cannot derive error scaling laws and that the error effects depend on the details of the errors, not just on the frequency spectrum of the errors. Fortunately, however, very short wavelength errors are not physically possible because of the finite vane separation; thus, random errors are not harmful for achievable error amplitudes. Slowly varying errors can be a problem for real machines. A slowly varying (or fixed) dipole field component will cause the beam to oscillate about an orbit that is not on-axis, causing a reduction in transverse acceptance and possible particle loss. This beam-offset effect occurs, even though the dipole field is oscillating in time, because it exists together with an in-phase oscillating quadrupole field. A voltage droop caused by an imperfect rf mode causes a reduction in the longitudinal acceptance. This reduction occurs because the synchronous phase is reduced in magnitude to maintain the design energy gain, which is fixed by the geometry (cell lengths).

CORRECTING CLOSED-ORBIT DISTORTIONS IN PSR

When the PSR is turned on, the beam will not follow the ideal orbit through the center of the beam pipe; probably it will follow a distorted closed orbit. The main contribution to the distortion will be misalignments of the magnets.

There are two theoretical problems associated with the closed-orbit distortion (COD): (1) Given a known set of misalignments, what is the COD? (2) Given a measured COD, which magnets are misaligned? The first problem is important in determining manufacturing and alignment tolerances. The second problem is important in reducing the COD after the machine is turned on.

At first sight, the problems seem complicated because there are 6 degrees of freedom per magnet, and there are 30 magnets for the PSR. There are two simplifications that help to reduce the size of the problems: There are only two degrees of freedom per magnet that affect the COD. The other degrees of freedom either do not affect the beam or only contribute to tune shifts or to coupling of small-amplitude modes of oscillation of the beam. Furthermore, one degree of freedom affects the radial COD and the other degree of freedom affects the vertical COD. This separation allows one to treat the radial and vertical distortions separately.

Experimentally, one can measure the COD at a small number (17) of points around the ring. One therefore has a set of 17 linear equations relating the observed orbit to the 30 magnet-displacement parameters. Therefore, there appears to be no unique solution to the problem of determining the misalignments from the COD. An excellent way of getting around this problem is to change the magnetic fields in all the quadrupole magnets and to remeasure the COD. The result is a double set of equations (34 equations in 30 unknowns) that can be solved in the least-squares sense.

This scheme has been implemented in two computer programs called CODINV and FITCOD. The program CODINV generates CODs from known magnet displacements and then tests schemes for inverting the COD and recovering the misalignments. The program FITCOD is a user-friendly version of CODINV that will be installed on the PSR control-system computer to aid the accelerator physicists in reducing the COD.

STABILITY OF THE SHORT-BUNCH OPERATING MODE IN PSR

The short-bunch, high-frequency operating mode of PSR is designed to accumulate and store six bunches of 10^{11} protons. The circulating bunches will be extracted one at a time. Because of the heavy beam loading, the voltage on the rf buncher cavities is dominated by the circulating beam current. To match the phases of the beam current and the voltage during the injection and extraction periods, a time-dependent, cavity-tuning scheme has been considered. Guidance is needed in the tuning speed and tuning function as well as an understanding of the stability properties of the system.

Progress has been made on analyzing the stability of the phase synchronization for the injection and extraction with cavity tuning. The analysis is

based on an equivalent circuit model. A set of coupled, nonlinear, differential equations was formulated for the voltage, the voltage phase, and the beam phase. Understanding the behaviors of bunching voltage and beam current caused by the injection and extraction with cavity tuning, as well as the requirements for cavity tuning for stability, was obtained by solving those differential equations numerically. For extractions, the results indicate that the stability will be maintained if the cavity resonant frequency can be properly tuned to match the beam current within 50 μ s after each extraction; the exact function the resonant frequency follows is not important. Improvement in reducing phase variations of voltage and beam current can be achieved by extracting a bunch at halfway in the cavity-tuning procedure. It is found also that the error allowance in the overtuning of the resonant frequency is more stringent when there are more bunches in the ring. For extracting one bunch out of six, only about 2% of overtuning can be tolerated. On the other hand, it seems we can tolerate undertuning errors up to 10%. For injection, we found that cavity tuning should follow the rapid linear rise of the beam current closely; a few per cent increase in tuning time may jeopardize the stability of the system.

LONGITUDINAL SPACE-CHARGE EFFECTS IN LAMPF II

As proposed, LAMPF II will be a rapidly cycling synchrotron that will accelerate a portion of the LAMPF beam from 0.8 to 32 GeV. Most of the magnet lattices proposed for transporting the beam around the ring result in transition at some energy less than 32 GeV at which the effective mass, as far as the rf accelerating system is concerned, appears to become negative. Experience with other high-energy synchrotrons indicates that the beam may become unstable after transition, with a large increase in longitudinal emittance. One source of difficulty is the longitudinal space-charge force. Before the transition, the longitudinal space-charge force tends to increase the equilibrium length of a bunch; after transition, the space-charge force leads to a smaller equilibrium bunch length. The bunch length after transition is larger than its equilibrium value and begins to undergo large amplitude oscillations. Nonlinear effects and a phenomenon called the negative-mass instability cause the emittance growth. The growth time of the instability at transition is proportional to the beam intensity. LAMPF II will have a very intense beam (100 μ A); therefore, it is important to simulate the effects of crossing the transition energy.

A code has been written to study the effects of longitudinal space-charge forces on the transition in LAMPF II. This code runs on the VAX; a typical run with 1000 particles through the full cycle takes about 4 h.

Runs with and without space charge and for various initial choices of $\Delta p/p$ show that longitudinal space-charge forces do not significantly affect either the transport around the ring or the longitudinal emittance after transition. Basically, this is because the bunching force of the rf accelerating system is much larger than the longitudinal space-charge force for the model of the synchrotron chosen.

SOLENOID OPTIMIZATION CODE

Emittance growth produced during the passage of the dc beam through a solenoid may prove troublesome for FMIT beam optics. The growth may be considered to be due to differences in focal point for particles traversing the solenoid lens at different radii. We are developing a computer code that attempts to reduce the emittance growth by finding a more optimum vector-potential distribution for the solenoid.

The approach used by the code is to set up an array of current loops about the longitudinal axis. These loops, which may carry constant or variable currents, produce the vector-potential distribution of the system. Particle orbits are integrated through the system to determine the focal-point range, and the variable currents are changed to shorten the range. The required improvements are found using a Nelder-Mead¹ optimization program. This technique allows the simultaneous optimization of quite large numbers of variables. Once the optimized vector potential is determined, POISSON or MIRT can be used to find more practical iron and coil geometries to produce the same field.

The code is working now in a rudimentary form, and survey work is in progress to determine the proper placement of the current loops. Future work will include the addition of space-charge effects and improvements to the input and output of the code.

POISSON GROUP CODES AND URMEL

At present, sets of the Poisson group codes on CCF LTSS machines and on the AT- and MP-Division VAXs are maintained by AT-6. Copies of these source programs, with a User Guide are supplied to any requestor who provides us with

a tape (usually we receive about two requests per month). In addition, assistance is provided for beginning users as well as limited help to users who are having problems with their particular run. This assistance is provided primarily to AT-Division personnel.

During this period, the following significant modifications and corrections have been done to the codes:

- The discrepancies that occasionally would occur in the POISSON field calculations, using first and/or second neighbors, have been corrected.
- The LATTICE and POISSON files were modified (AT-3 VAX only) to calculate the current associated with fixed-potential points and the total current and energy. These features already were available on the LTSS codes.
- The corrections to the stacking factor that had been put into POISSON earlier were incorporated (only on LTSS codes, so far).
- Additions to FISH were made to allow users the option to read in H_ϕ normalization factor that is used in the energy and power calculations. These additions are available only on LTSS codes, but will be implemented on the VAX versions at the earliest opportunity.

During the summer of 1982, T. Weiland from the Deutsches Elektronen Synchrotron, Hamburg, W. Germany, visited Los Alamos for three weeks and developed the first version of URMEI, a code for calculating the resonant frequencies and fields of cylindrically symmetric cavities. This code, in its refined versions, calculates arbitrary azimuthal variations ($\cos m\phi$ or $\sin m\phi$ dependence, $m = 0, 1, 2$, etc.). The code uses a variable rectangular mesh with triangular fill and solves a linear eigenvalue problem. The method finds the lowest eigenvalues in order, always starting with the lowest, and is guaranteed to find all the eigenvalues.

REFERENCE

1. D. M. Himmelblau, Applied Nonlinear Programming (McGraw-Hill Book Company, New York, 1972).

ACCELERATOR TEST STAND (ATS)

INTRODUCTION

During this period, AT Division's second RFQ became operational. The new accelerator was designed to accelerate greater than 100 mA of H^- from 0.1 to 2.0 MeV with minimal emittance growth. Operating frequency was 425 MHz and the structure is manifold driven as was the POP.

The overall length of the new RFQ is 2.89 m. This length made rf tuning of the structure a difficult process because of alignment sensitivities proportional to (L^2/λ^2) , a relationship discovered in the tuning process. Here L is the structure's overall length and λ is the electrical wavelength.

The RFQ as previously tuned was installed on the ATS in July. Installation of all cooling systems, vacuum systems, and RFQ systems was completed in August. The rf power was applied for the first time August 12; tuning of the rf system, required to match the rf power supply to the RFQ, was completed with 1-kW power applied August 12. Power conditioning of the RFQ was accomplished in a very short time with a 775-kW forward power and 700- μ s pulse width at 10 Hz being achieved August 27. The RFQ operating in this mode demonstrated stable operation after being advanced through a number of power levels where fast discharges were observed, followed by zones of stable operation. The RFQ vacuum levels observed throughout the conditioning process ranged from a minimum pressure of 3 to 4 $\times 10^{-8}$ torr to a maximum of 5.8 $\times 10^{-7}$ torr during rf structures discharge. The conditioned RFQ was integrated into the ATS beam transport and was placed in operation September 3. Figure 14 shows an overall view of the ATS RFQ assembly.

Initial beam was accelerated by the RFQ on November 16, 1982. By operating the accelerator at considerably above rated power, full-energy acceleration was achieved. The accelerator as mounted on the ATS contained vane voltage distributions that were far from ideal. The abnormal vane-voltage distribution provided an excellent test of our ability to predict RFQ performance for large parameter perturbations. A comparison of measured and predicted transmissions is shown in Fig. 15.

As a consequence of the vane-voltage distribution and the increased rf power levels employed, significant portions of the structure were operated at vane-voltage levels exceeding 2.5 times the Kilpatrick criterion. The ability to sustain these voltage levels indicates that the designed voltage for the new

Fig. 14.

The power ratio is the RFQ operating power divided by the designed power level of 550 kW. Data for the dashed and dotted curves of beam current transmission above 1.1 MeV and 1.7 MeV, respectively, were measured with energy-degrading foils. Foil transmission curves have been folded into the data shown.

Fig. 15.
ATS RFQ assembly.

RFQ, 2.06 times Kilpatrick, may be a conservative figure and that increased voltages in the RFQ structure may be possible. This could make possible higher current limits or shortened RFQ accelerators without sacrificing output energy. Further voltage-holding tests on RFQ structures are in progress.

The new RFQ is scheduled for extensive modifications early next year. In addition to mechanical changes designed to reduce alignment difficulties, vane coupling rings based on the Berkeley design¹ will be installed. Reassembly and resumed tests are expected in mid to late 1983.

We go on to describe in detail the ion source and injector work done during this period and also discuss improvements on the ATS RFQ simulation code.

ION SOURCE AND ATS INJECTOR

ATS Injector

A substantial effort was directed toward injector operation, maintenance, and improvements, for example, to the gas controller and the extractor regulator. The most troublesome operational problem has been the long conditioning time required to get good operation with new source parts. A spare source with an external cesium supply has been built for preconditioning. With the external supply, the cesium cycling time should be several hundred hours instead of the present thirty.

The emittance of the injector beam always has been substantially higher than that from the prototype source on the ion source test stand. Also, the projection of the 20-keV emittance measured at ES1 (see Fig. 16 for a plan view) back to the source did not give beam radii corresponding closely to the beam size at the emission slit: $r_x = 5$ mm, $r_y = 0.25$ mm. Calculations showed that there should be emittance growth in the electromagnetic quadrupole before the emittance-measuring station and that this could be reduced by installing a permanent-magnet (PM) quadrupole between it and the bending magnet; however, emittance was about the same before and after installing the PM quadrupole.

We also noted that the phase-space density, as observed by the emittance-scanner currents, had much greater fluctuation than the beam current itself and that the amplitude of fluctuations was progressively larger farther along the transport. Dzhabbarov recently reported beam-plasma oscillations produced by an H^- beam with conditions similar to those in the ATS injector; he showed

Fig. 16.
Plan view of the ATS injector.

that the oscillations in current density were damped at high gas pressures in the transport line.² Normally we use xenon at a density of about $6 \times 10^{11}/\text{cm}^3$, for which the stripping losses are 0.25%/cm. In accordance with Dzhabbarov's results, we examined the effects of much higher density. The emittance scanner was positioned in the beam center; the scanner current, proportional to $d^2i/dydy'$, was recorded for 50 beam pulses for low and for high xenon density. Substantial reduction in pulse-to-pulse fluctuations was observed (Fig. 17), along with a rotation of the phase space. The extracted current did not change significantly with xenon density and had ± 5 to 10% fluctuations. For these gas flows, the emittance versus beam-fraction data for the y-plane are shown (Fig. 18). The rms emittance was measured in both planes as a function of xenon density; results are shown in Figs. 19 and 20. In the y-plane, the emittance can be reduced by the factor 3; in x, by the factor 1.5. Smaller x-plane emittance has been observed at a different quadrupole tune, and we plan to explore the tune dependence further.

Holmes's theory³ of quiescent neutralization for positive ion beams was extended to negative beams, and the residual potential well for a 100-mA,

Fig. 17.

Variation of beam properties with low and high xenon densities at ES1, the 20-keV emittance scanner. Shows extracted current, phase-space contour, and phase-space density variations for 50 consecutive beam pulses.

Fig. 18.
Emittance versus beam fraction in y-plane at 20 keV for low and high xenon densities.

Fig. 19.

The rms normalized emittance in y-plane versus xenon density at 20 keV.

Fig. 20.

The rms normalized emittance in x-plane versus xenon density at 20 keV.

20-keV H^- beam in xenon was calculated for various beam radii (Fig. 21). The relative electron density in the beam is given in Fig. 22. For a 1-cm beam radius, the well is ~ 4.5 eV positive, giving an effective positive beam current of about 1 mA (a net focusing force for the beam). Because the quiescent theory of neutralization of either Holmes or of Gabovitch gives overneutralization of a negative beam, the correct sign of the current to be used in, for example, the Kapchinskii-Vladimirskii equations is positive. A negative effective current would correspond to a defocusing force, but this is not possible in the quiescent case for negative beams. As a result of fluctuations, either inherent in the beam current or as a result of beam-plasma instabilities, it is clear from our measurements that the effective current does fluctuate. As a first step in assessing the magnitude of this effect, we calculated the orientation of the phase ellipse at the emittance scanner for various values of effective current between the scanner and the end of the extractor, assuming that the fluctuations did not affect the orientation of the phase ellipse at extraction. From the measurements at ES1 for high xenon density, we projected the beam phase space back to the source with TRACE (using four times the rms emittance and zero effective current) and found that the beam was near a waist in both planes with radii of $r_x = 4.8$ mm, $r_y = 0.6$ mm, close to the expected values. The beam then was projected forward for various effective currents I_{eff} to deduce the sensitivity of phase-space orientation to current. The calculated phase spaces at ES1 are shown in Fig. 23 for I_{eff} equal to ± 3 mA. A formula was derived for the rms emittance of two superposed ellipses of uniform current density, and the calculated rms ellipse is shown on the same plots. The emittance growth factor as determined by this method is shown as a function of I_{eff} (Fig. 24). A value of $I_{eff} = 3$ mA would account for our measured emittance growth (Figs. 19, 20). The neutralization time constant for H_2 at 10^{-4} torr is 10 μ s; for xenon at 2×10^{-4} torr it is 1 μ s. The beam current at extraction typically fluctuates about $\pm 10\%$ or ± 10 to 15 mA; thus, we expect that fluctuation frequencies higher than 100 kHz could cause the emittance growth in the absence of xenon. Frequency-spectrum analysis of the extracted current does not show any pronounced frequencies, but further measurements are required.

Fig. 21.

Calculated beam-potential drop versus xenon gauge pressure for 100 mA of 20-keV, H^- ions for different beam radii. Calculated from Holmes's theory modified for negative beams.

Fig. 22.

Ratio of electron density to beam density for 100 mA of 20-keV, H^- ions in xenon gas. Calculated from Holmes's theory.

Fig. 23.

Beam-transport calculations, using TRACE, between source and ES1. With high xenon density, the measured phase space at ES1 projected back with zero current to the source gives nearly the physical slit size. When projected back to ES1 with an effective current of +3 mA or -3 mA, the phase spaces do not overlap, resulting in an effective increase in emittance.

Circular-Aperture Source Design

With the present ATS injector source, the H^- beam is extracted from a 10- by 0.5-mm² slit. The resulting asymmetry in emittance is quickly lost because of coupling of the planes in the 90° magnet and, in any case, would be lost in the RFQ. Extraction from a circular emitter is desirable to produce a beam of minimum emittance (proportional to radius) with the lowest current density (proportional to the power density in the discharge), which is a possible limitation for dc operation. For the calculation of positive ion trajectories extracted from a plasma, several codes have been written, including WOLF,⁴ AXCEL,⁵ and SNOW.⁶ The SNOW code, developed at Sandia and in use at Los

Fig. 24.
Emittance growth calculated by
the above method versus fluc-
tuations in effective current.

Alamos, assumes a collisionless plasma with electrons in a Boltzman equilibrium with the ions. A finite number of ion rays are traced through the plasma and system of electrodes, with the potentials at all points calculated by a self-consistent relaxation process with fixed conditions along the boundary and electrodes. Although all of these codes have been well-tested for their zero- and first-order predictions (total current and envelope divergence), there have not been, to our knowledge, comparisons with analytic models for second-order (emittance) predictions. Of special concern is that the overall accuracy be adequate to make this calculation. For this purpose, an rms emittance calculation was added to SNOW.

First we studied a "perfect" Pierce case as a bench-mark calculation (Fig. 25). Plasma originates at the injection plane (in this case coincident with the plasma electrode) with ions having arbitrarily chosen longitudinal and transverse velocities, and with the extraction electrode having no opening, thus eliminating equipotential distortions there. The computer calculation differs somewhat from an analytic calculation.

PIERCE ELECTRODES

25kV, 13.2mA

141 x 81 matrix, 0.2mm/matrix square

$T_e = 0.1\text{eV}$, $T_i = 10\text{eV}$

Fig. 25.
Perfect Pierce test case.

To test SNOW's calculation of emittance, two types of distribution (Fig. 26) were injected into the perfect Pierce case.

1. Uniform divergence—at each radial point, rays with angles 0 , $-\theta$, and $+\theta$ having equal currents were injected, where $\sin \theta = T_{\perp}/T_i$, $T_{\perp}$ being the transverse energy and T_i being the injected energy.

2. Maxwellian—at each radial point, 10 rays of equal current were injected with angles chosen so that the rms transverse velocity of the distribution was $T_{\perp}/M$. The spatial density was taken to be uniform. For these distributions, the rms emittance at emission is given in Fig. 26.

The percentage deviation of the SNOW calculations from these formulae was calculated over a range of parameters. For Distribution 1 the agreement was very good when $T_{\perp}$ was kept constant and T_i was varied (Fig. 27), or when $T_{\perp}$ was varied and T_i was kept constant (Fig. 28). For the Maxwellian case with fixed $T_{\perp}$, the agreement was good over a range of T_i (Fig. 29). In summary, the calculations have adequate accuracy and are in good agreement with test cases.

UNIFORM MODEL

Equal current rays for $-\theta$, 0 , $+\theta$
divergence; uniform radial distribution

$T_{\perp} = T_i \sin^2 \theta$, T_i = injected ion energy

Here, $\epsilon = r \sqrt{T_{\perp}/3MC^2}$

MAXWELLIAN MODEL

Equal current rays for 10 angles

$$\langle \dot{x}_i^2 \rangle = \frac{\int_{\dot{x}_{i-1}}^{\dot{x}_i} \dot{x}^2 f(\dot{x}) d\dot{x}}{\int_{\dot{x}_{i-1}}^{\dot{x}_i} f(\dot{x}) d\dot{x}}$$

where $f(\dot{x}) = e^{-M\dot{x}^2/2kT_{\perp}}$

$$\text{So, } \epsilon = r/2 \left(\sqrt{kT_{\perp}/MC^2} \right)$$

Fig. 26.
Test of emittance
calculation in SNOW.

Fig. 27.

Deviation of uniform divergence calculations from theory versus ion injection energy; transverse energy held constant.

Fig. 28.

Deviation of uniform divergence calculations from theory versus transverse energy; ion injection energy held constant.

Fig. 29.

Deviation of Maxwellian distribution calculations from theory versus ion injection energy; transverse energy held constant.

Our goals for a circular extractor design are

- current of 150 mA,
- extraction field a maximum of 120 kV/cm,
- an acceptably low emittance, and
- acceptable beam divergence— ~ 100 mrad or less.

We assume an H^- ion temperature of 4 eV, the upper limit for the Dudnikov source as deduced by its emittance; for this, a minimum current density would be 0.22 A/cm^2 . As a starting point, the Langmuir-Blodgett equations for spherical flow were combined with the Davisson-Calbick equation for extractor defocusing, modified according to Wilson.⁷ From this, the design shown in Fig. 30 was studied; the parameters are given in Table IV.

Fig. 30.
Calculated properties of spherical extractor with zero ion temperature and 10-eV injection energy.

TABLE IV

SPHERICAL PIERCE DESIGN PARAMETERS

Voltage	29 kV
Current	151 mA
Emittance	acceptably low
Current density	0.66 A/cm^2
Emitter radius	0.27 cm
Injected ion temperature	0.0 eV

Most of the optical aberrations occur at the emission surface, and they can be reduced by making the plasma electrode thinner or by making the injected ion energy larger, the latter normally not readily variable experimentally. With a 4-eV ion temperature, an artificially high ion energy of 100 eV was required to avoid nonuniform current-density build-up in the plasma, but the emittance was still acceptable (Fig. 31). Finally, for variations in current of $\pm 10\%$, the resulting phase-space orientations overlap sufficiently that the time-averaged emittance growth would be only a few per cent at extraction.

Circular-Aperture Source Scaling

The pulsed ATS injector source can produce a beam of up to 3.5-A/cm^2 current density, but the power density in the discharge ($\sim 10 \text{ kW/cm}^2$) prevents extension of the duty factor to dc. The measured emittance is compatible with a 4-eV ion temperature. In this case, it should be possible to produce a 150-mA beam from an 11-mm-diam aperture with a 160-mA/cm^2 current density and a low emittance. Scaling the source according to the laws of similarity for gas discharges would result in $\sim 0.5\text{-kW/cm}^2$ internal power densities, in the range of conventional cooling technology for dc operation. The cathode gap would have to be increased from the present 4 mm to ~ 8 cm; however, it seems likely that a full scaling would not be necessary for a pulsed source. The present source housing cannot accommodate a large expansion, but cathodes were made with gaps of 2.7, 4.3, 8.4, and 11.3 mm. Although this is not a simple

Fig. 31.
Calculated properties of spherical extractor with 4-eV ion temperature and 100-eV injection energy.

scaling, we found that the required gas pressure varied nearly inversely with this dimension, as expected. Through a 2-mm aperture, 25 mA was extracted, a 0.8-A/cm^2 current density, but electron loading prevented successful extraction with a 5-mm aperture. Because these experiments were carried out on the ATS injector, limited time was available and no further work has been done. From previous work with circular apertures for the early injector configuration of 250 kV, 30 mA, we found that the beam emittances were nearly the same in both planes: $0.003\pi\text{ cm}\cdot\text{mrad}$ for a 1.5-mm-diam aperture. This simple set of measurements indicates that the basic scaling is sound but that some care is required to maintain proper operation. A cathode gap of at least 4 cm is probably required to get reasonable gas efficiency. A new housing would have to be built, but the present 90° magnet probably could be used. A more attractive long-term goal would be to use PMs for the source field and begin focusing the extracted beam as soon as possible with quadrupoles or a solenoid. From the ion-acoustic model of the plasma oscillations, the scaling would result in oscillation frequencies around 1 to 2 MHz. Understanding and damping of these oscillations might be easier in a large-scale source, but the problem seems likely to be a continuing one.

Ion Source Test Stand

Work on the ion source test stand (ISTS) was carried out (using our original Dudnikov source) to determine parameters, to understand the coherent and noise fluctuations in the source and in the beam, and to make measurements to gain an improved understanding of the source plasma. In addition, a small theoretical effort was devoted to plasma modeling, the conclusion of which was that measurement of the relative spectral intensities from excited states of the hydrogen atoms probably would not be easily related to the translational energies of the atoms. This energy is of interest because the H^- ions extracted are believed to have the temperature of the atoms, and the H^- emittance is consistent with a 4-eV temperature. Because of the small plasma size, most of the emitted light escapes from the plasma; hence, the intensities reflect the spectrum of electron energies and the excitation cross sections, not the atom energies. The primary production mechanism for excited atomic states is presumed to be from collisions with electrons in the tail of the Boltzman distribution.

The H^- ion temperature deduced from an emittance measurement includes the effects of extraction and transport aberrations; however, the deduced temperature should scale with energy for an aberration-dominated system instead of being invariant as for a true temperature. Also, we expect the positive ions to have different temperatures from that of the H^- ions. We measured the currents and emittances of H^+ , H^- , H_3^+ ions from 4.4 to 13 keV for dc operation so that space-charge forces would be small. The positive currents were mostly H^+ and H_3^+ ions and were about the same magnitude as the H^- current. If the source plasma potential is negative, as suggested by Dudnikov,⁸ then the positive ion current at emission would be much less than that in the plasma; therefore, this probably is not an indication of the source-plasma density but indicates that positive ions diffuse outward to maintain neutrality in the H^- rich plasma. Unfortunately, the emittance data were taken over a period of a few days and had inconsistencies that tended to mask the variations for which we were looking. A tentative conclusion is that our emittance is dominated by aberrations, but this experiment must be more systematically done when the emittance scanner on the test stand is computer automated.

Discharge voltage and current waveforms for the 100-A pulsed discharge have been observed to have large amplitudes of coherent oscillations in the 10- to 20-MHz range (Fig. 32). As reported previously, these oscillations decrease in frequency during the pulse, often in discrete jumps. Primarily they are seen in the voltage, probably because the discharge is driven by a quasi-constant current generator. Only random fluctuations (noise) are seen with a 1-A, dc discharge, but the noise disappears below a critical magnetic field B_c . The pulsed discharge generally will not operate below this field, but noise decreases as it is approached. The influence of all these oscillations on beam emittance is not fully understood, but previous measurements have shown that the emittance can drop a factor of 3 when noise is minimized.

The predicted dependence of oscillation frequency on discharge parameters is shown, summarizing the results of an ion acoustic-wave model (Fig. 33). We examined the frequency dependence on the parameters shown in Fig. 34; the results (Fig. 35) are in reasonable agreement with theory. We have not modeled $E_{\max}$ theoretically, but the value of ~ 10 eV determined from the formula is in rough agreement with the plasma potential, -20 V, as determined by Dudnikov.⁸ There appears to be negligible dependence on W , the slot width, and on B , the magnetic field. It is suggested that with a cylindrically symmetric slot and

Discharge Voltage Waveforms

Discharge Frequency Spectra

Fig. 32.
Discharge oscillations study.

$$f = \frac{2n}{L} \sqrt{\frac{E_{\max}}{M}}, \quad \text{where} \quad \begin{aligned} f &= \text{Oscillation frequency} \\ n &= \text{Integer} \\ E_{\max} &= \text{Electron energy at the maximum of the electron velocity distribution} \\ L &= \text{Cathode - Cathode spacing} \\ M &= \text{Ion mass} \end{aligned}$$

Fig. 33.
Ion acoustic model.

Cross Section of Penning Source

- L, the cathode - cathode spacing
- M, the ion mass

Also

- W, the arc slot width
- B, the magnetic field
- Q, the discharge gas feed rate (H_2 or D_2)
- I_d , the discharge current

Fig. 34.
Parameters varied in oscillations study.

Parameter	Effect on Oscillation Frequency f	Quantitative Result	
L	Approximate $1/L$ Dependence	$\frac{1/L, \text{ mm}^{-1}}{.12}$	$\frac{f(\text{MHz})}{7.8}$
		.23	13
		.37	20
M	Approximate $1/\sqrt{m}$ Dependence	$\frac{1/\sqrt{m}}{H_2 .707}$	$\frac{f(\text{MHz})}{12}$
		$D_2 .5$	10
W	Minimal	$\frac{W(\text{mm})}{2}$	$\frac{f(\text{MHz})}{12.4}$
		3	12.1
B	Very Weak Dependence	A +29% change in B causes a -2.3% change in f .	
Q	Moderate Dependence	A +53% change in Q causes a -17% change in f .	
I_d	Moderate Dependence	A -60% change in I_d causes a +25% change in f .	

Fig. 35.
Results of oscillations studies.

magnetic field, the oscillations can be suppressed. Emittance measurements will be an important part of this study.

To investigate the possibility that source pulsing below B_c was not possible because of discharge start-up difficulties, a circuit was devised that maintained a 1-A, dc "keep-alive" arc on which a pulse could be superposed. We found that at a field less than B_c , the pulse current would not exceed more than a few amperes but that high-current operation was possible as usual, above B_c . A study with hydrogen and deuterium discharges with four different source geometries has shown that $B_c W / M = 238 \text{ G}\cdot\text{cm}$ within $\sim 10\%$ for our source, where $M = 2$ and 4 , and W is the anode width (Fig. 35). This would be consistent with a plasma ion (H^+ or D^+) energy of 1.4 eV . Our interpretation is that with a field lower than B_c , the Larmor radius of the ions is too large for them to return to the cathode; hence, the arc stops. In dc operation at low current, there probably are lower ion energies and different species in the plasma. We conclude that the pulsed discharge will not operate at the low field that quiets the dc discharge. Nonetheless, there was substantial reduction in the discharge and beam-current noise near B_c for the pulse discharge, and the keep-alive circuit made it possible to operate reliably near this field. It was possible to extract a beam with only $\pm 2\%$ fluctuation in a bandwidth in excess of 10 MHz , substantially less noise than the $\pm 10\%$ for typical operation (Fig. 36). The discharge voltage still has coherent oscillations; therefore, these have no apparent effect on the current. If the emittance turns out low, then we should try to achieve this operation without the keep-alive circuit so that the injector source can be operated in a similar manner. Without the keep-alive arc, it was possible to produce a pulsed discharge with no coherent oscillation and with low noise over a narrow range of gas flow and magnetic field (Fig. 37). Thus, there are operating regimes for which a promise of lower current fluctuation and beam emittance may be realized.

High-Current Test Stand

Some source development work has been done during the year on the ATS injector; however, the injector is becoming increasingly devoted to transport and matching studies between the column and the RFQ. The ISTS can be used to continue development and conditioning of parts for the injector, but its power-handling capability is insufficient for dc source development. For these

USED A DC "KEEPER" ARC TO PRODUCE QUIET ($\leq 2\%$ FLUCTUATIONS) H^- CURRENT PULSES NEAR THE CRITICAL MAGNETIC FIELD B_C . NORMALLY HAVE $\pm 10\%$ FLUCTUATIONS.

PULSED CURRENT	80 A
DC CURRENT	1 A
B	1100 G
GAS FLOW	125 STD CM^3/MIN
EXTRACTION VOLTAGE	11 kV

± 80 V, 17 MHz COHERENT OSCILLATIONS ON VOLTAGE PULSE.

Fig. 36.
Production of quiet H^- current pulses near the critical magnetic field.

HAVE PRODUCED PULSED DISCHARGES WITHOUT NOISE OR COHERENT OSCILLATIONS (NO "KEEPER" ARC) - VOLTAGE FLUCTUATIONS LESS THAN $\pm 5\%$ FOR LAST 550 μs OF PULSE.

FOR H_2 THERE IS A NARROW BAND OF GAS FLOW (70 - 100 SCCM) AND MAGNETIC FIELD (1410 - 1850 G) WHERE THE QUIET VOLTAGE PULSE WILL RUN.

WORK IN PROGRESS TO UNDERSTAND PRODUCTION OF QUIET DISCHARGES AND TO MEASURE THE RESULTING H^- BEAM EMITTANCE.

Fig. 37.
 Production of quiet discharge-voltage pulses.

reasons, construction of a high-current test stand (HCTS) has been started so that source discharge power levels of 20 kW, estimated for the rotating ion source (RIS) or a cusped-field source (CFS), are available at 30-kV potential. The basic capabilities of the HCTS, as determined by equipment now on hand, are given in Fig. 38. The isolation transformer is a standard design for 250-kV isolation, 50-kVA power, and it costs little more than a lower voltage unit; however, it also can be used as a spare for the ATS injector transformer. Many of the components for the HCTS are on hand (Fig. 39) as a result of purchases and surplus acquisitions. A recent photograph of the installation is shown in Fig. 40. The floor plan is shown in Fig. 41. Further work on the HCTS has been delayed pending further funding.

- H⁻ CURRENT - 100 mA, 100% Duty Factor
(limited by power supplies
and cooling considerations)
- POWER - 50 kVA (limited by isolation transformer)
- GAS FLOW - 2 torr • l/s (limited by pumps)
- VOLTAGE - 30 kV (limited by power supply)

Fig. 38.
The HCTS design features.

ON HAND

- Diffusion Pump System (10,000 l/s for H₂)
- Isolation Transformer (50 kVA, 250 kV)
- Extraction Power Supply (30 kV, 500 mA)
- Arc Power Supply (250 V, 50 A)
- Some Electronics Modules
- Electronics Racks, HV Cage, and Support Stand

TO BE PROCURED

- Valve - Baffle Combination
- Vacuum Box
- Diagnostics
- Other Electronics Modules and Power Supplies

Fig. 39.
The HCTS status.

Fig. 40.
Photograph of the HCTS.

Fig. 41.
Plan view of the HCTS.

Considerations for a dc Source

In the original concept of the RIS, it was assumed that the asymmetry in emittance of a beam extracted from a slit emitter could be preserved and that the resulting useful brightness would be inversely proportional to $\epsilon_x \epsilon_y$. The RIS uses rotating electrodes to spread discharge power density, estimated to be 10 kW/cm^2 pulsed in the Dudnikov source, over the electrode's periphery and to keep average heat loads under 1 kW/cm^2 . A localized magnetic field keeps the discharge confined to a peripheral distance of ~ 1 to 2 cm , determined by the magnetic pole separation, that must be somewhat larger than the cathode gap. Although this seems reasonable for a slit beam, the power efficiency would be much less for a circular beam because the cathode gap must be increased, thus spreading the discharge peripherally while simultaneously using a smaller peripheral region for ion extraction. Inevitable coupling of the x- and y-planes as the beam is propagated has led us to conclude that a circular aperture should be used for the brightest beam with the minimum current density. With the present emittance goal, the projected power density in the source is reduced from previous requirements; therefore, a large-scale version of the Dudnikov source could approach the dc goal.

Elsewhere, development of other sources with focusing cathodes (self-extraction) has led to substantial improvement in their power efficiencies over the past few years. Last year we tested a grooved magnetron source on loan from BNL because it had a possibility of meeting our dc goal; however, the emittance we measured was much larger than could be accounted for by elementary source considerations. This large emittance was attributed to source-plasma oscillations, which were much higher than for the Dudnikov source. At present we do not have a specification for the allowable amplitude and frequency of current fluctuations; if fluctuations must be kept under a few per cent, it may be necessary to use a source with no magnetic field, one successful version of which is the CFS.

The CFS developed by Leung and Ehlers has produced a quiescent, 1-A, dc H^- beam over a large area, the current at the converter surface having a density of ~ 10 mA/cm².⁹ This can be focused to higher density for extraction, but the sputter energy at the converter would have to be low to produce a beam of sufficiently low emittance. This sputter energy is not known, but there is evidence that it is 1 to 5 eV. By collimating the converter-produced beam at extraction, it is possible to reduce the emittance, as has been done for LAMPF for a pulsed 10- to 20-mA version of the CFS. In its present state of development, this type of source probably could produce 25-mA dc within our emittance requirement.

To increase the current, the plasma density might be increased. This would require better cooling, more efficient magnetic confinement, and longer filament lifetime. Use of a larger converter and more collimation would help also. With a larger converter, enough primary electrons might be produced to solve the filament problem. There is much to be learned about this source, including the sputter energy and its dependence on operating parameters, optimum coating of cesium on the converter, and optimum converter voltage. An interesting question is whether, as a pulsed source (for which heating limitations can be overcome), a quiescent beam of adequate current can be extracted. It may be possible to examine this possibility with the LAMPF source. Development of a suitable dc source can be carried out on our HCTS, now partially completed.

ATS THEORETICAL SUPPORT

ATS RFQ Simulation-Code Improvements

The ATS RFQ simulation code, a three-dimensional space-charge calculation, has been further improved. Because the space-charge calculation is so time consuming, a multistep procedure was incorporated in which space-charge information is stored for one period. This procedure makes it possible to compute space-charge forces approximately once per period yet take into account the variation, over a period, in these forces. What is neglected here is the change in the variation over the period, not the variation itself.

Integrators suitable for simulations of periodic systems were investigated. High-order methods that take advantage of the near-Floquet form of the solution were not successful because of stability problems. (Making such methods canonical is not easy.) We were, however, able to improve the simple semi-implicit formula by adding two free parameters. Accuracy is adequate for simulations up to ~ 200 rf periods using only 8 integration steps per period.

The beam transport code, TRACE, has been improved and documented with an extensive "HELP" package that furnishes information necessary for using all aspects of this code. The TRACE model is being tested by comparing the TRACE emittance predictions with the measurements made on the beamline. With the use of overlay computer techniques, we now have real-time graphic display of the data as they are being collected. The analyzing code REANL is operational and, in addition to giving relevant ellipse parameters of the beam, gives graphics displays of the data.

Results of Simulations

RFQ phase-space acceptance was calculated by first producing a beam matched to the RFQ at a point where the beam is bunched. This match was accomplished by adiabatically deforming a beam matched to harmonic oscillator external forces. Then this beam was traced back through the buncher to the input of the RFQ; no particles were lost. This result is useful for several reasons. First, the momentum acceptance turned out to be $\sim 3\%$, which means several ion sources could be used to feed the RFQ simultaneously if an ion source of the required emittance could not produce enough current. The slight tilt of the axial phase-space ellipse indicates that the radial matching

section could be improved slightly or that the input beam should be modified slightly to match the RFQ acceptance parameters better.

It is simpler to machine RFQ vanes with a constant pole-tip radius. Such geometry, however, introduces a dodecapole ($n = 6$) term in the electric fields. An investigation revealed that the effect of the dodecapole term on the dynamics was negligible. (The effect on off-axis beams was not considered, however.)

Inverse-Problem Calculations

Paul Channell's method¹⁰ for solving the inverse problem in dynamics has been applied to the RFQ matching section. The problem is to determine the physical system required for transforming a beam matched to a space-dependent focusing system into a beam that is matched to a time-dependent focusing system. The theory is simple to apply, unless we also apply the constraint that the forces in the matching section are proportional to $\cos(\omega t)$ so that the matching section really is part of the RFQ structure. The resultant nonlinear algebraic equations were solved with a nonlinear optimizer; however, because of the large number of nonlinear variables, good solutions were difficult to obtain. An improvement is being worked on to reduce the large number of nonlinear algebraic equations into a few one-dimensional boundary-value problems. In this way, the nonlinear optimizer is still needed to solve the boundary-value problems, but the number of nonlinear variables is reduced greatly.

Fast RFQ Simulation Code for Design Work

A new RFQ simulation code was created by inserting a simple space-charge algorithm into the ATS RFQ simulation code. The linear and cubic parts of the space-charge forces are calculated, at every time step, in terms of particle moments. Thus, the calculation is three-dimensional but only approximate. Both straight simulations and production of well-matched input distributions by adiabatic deformation can be performed. The simulations run quickly and are believed to be sufficiently accurate except in the bunching region where fifth-degree terms in the space-charge forces should be included. The new code produces plots of the rms beam sizes at fixed times in the rf phase; therefore, simulations with matched beams will have smooth graphs. New configurations in the parameter variation in an accelerator can be tested to

see if they introduce a mismatch. Mismatches are to be avoided because they can lead to emittance growth and particle loss.

The design procedure is the following: start with a certain accelerator and produce a well-matched input beam with the new code by adiabatic deformation, then vary the accelerator parameters as a function of distance along the machine, with the goal of improving some characteristic (such as reduced overall length) while making sure that such changes do not introduce a significant mismatch anywhere in the machine. Experience with adiabatic deformation matching has shown that simple adiabatic arguments are of no value in analyzing this situation because, even with a fixed tune, the exact nature of the parameter variation is very important.

REFERENCES

1. "Improved Field Stability in RFQ Structures with Vane Coupling Rings," H. Lancaster, and H. R. Schneider, 1983 Particle Accelerator Conf., Santa Fe, New Mexico, March 21-23, IEEE Trans. Nucl. Sci., 30, No. 4, p. 3007 (August 1983).
2. D. G. Dzhabbarov and A. Naida, "Spatial Development of the Instability of a Dense Beam of Negative Ions in a Rarefied Gas," Inst. of Physics, Ukrainian Academy of Sciences, Zh. Eksp. Teor. Fis. 78, 2259-2265 (June 1980).
3. A. J. T. Holmes, "Theoretical and Experimental Study of Space Charge in Intense Ions Beams," Phys. Rev. A, 19, No. 1, 389 (January 1979).
4. W. S. Cooper, K. Halbach, and S. B. Magyary, "Computer-Aided Extractor Design," Proc. 2nd Symp. Ion Sources and Formation of Ion Beams, Berkeley, California, October 22-25, 1974, p. II-1.
5. J. H. Whealton, "Ion Extraction and Optics Arithmetic," Nucl. Instrum. Methods 189, No. 1, 1 (October 1981).
6. Jack E. Boers, "SNOW - A Digital Computer Program for the Simulation of Ion Beam Devices," Sandia National Laboratories report SAND-79-1027 (August 1980).
7. Robert G. Wilson and George R. Brewer, Ion Beams with Applications to Ion Implantation, (John Wiley & Sons, New York, 1973).
8. V. G. Dudnikov, E. G. Obrazovskii, and G. I. Fiksel, "Emission Properties of the Electrodes of Surface-Plasma Sources and Efficiency of H⁻ Production," Inst. Nucl. Physics, Siberian Branch, Academy of Sciences of the USSR, Fiz. Plazmy 4, 662-667 (May-June 1978).

9. K. N. Leung and K. W. Ehlers, "LBL Self-Extraction Negative Ion Source," Lawrence Berkeley Laboratory report LBL-13261 (August 1981).
10. P. J. Channell, "Explicit Suspensions of Diffeomorphisms--an Inverse Problem in Classical Dynamics," submitted to J. Math. Phys., Los Alamos National Laboratory document LAUR-82-1658 (June 1982).

PUBLICATIONS (July--December 1982)

G. P. Boicourt, "A Fast, Efficient Algorithm for the Solution of the Maximum Likelihood Equations of the Three Parameter Uncensored Generalized Gamma Distribution," submitted to IEEE Transaction on Reliability, LA-UR-82-2271.

P. Clout, "CAMAC Automated Measurement and Control Primer," Los Alamos National Laboratory document LA-UR-82-2718 (February 1982).

R. K. Cooper, "Proceedings for the LAMPF II Synchrotron Workshop," LA-9511C, LAMPF II Synchrotron Workshop, February, 1982.

R. A. Jameson, "Status of the FMIT Accelerator," EPRI Symposium on Accelerator Breeder Technology, June 9-10, 1982, Palo Alto, California, LA-UR-82-1623.

J. Muller, A. Schempp, "On the Drive for the Hf Quadrupole Structure," Translation, LA-TR-82-28 (1982).

H. A. Sandmeier, M. E. Battat, G. E. Hansen, "How to Calculate Effects of Tactical Low-Yield Enhanced-Radiation and Fission Warheads," Los Alamos National Laboratory report LA-9434, (October 1982).

H. A. Sandmeier, M. E. Battat, "Radiation to Personnel from Activities Induced in Tank Armor for Enhanced-Radiation and Fission Nuclear Weapons," Los Alamos National Laboratory report LA-9492-MS, (December 1982).

P. J. Tallerico, "Progress in the Gyrocon Deflection-Modulated Amplifier," Proc. 1982 Int. Electron Devices Meeting, Dec. 13-15, 1982, San Francisco, California, Los Alamos National Laboratory document LA-UR-82-2727.

P. J. Tallerico, "The Gyrocon Radio-Frequency Generator for FY-80 and FY-81," Los Alamos National Laboratory report, LA-9500-SR (September 1982).

D. W. Reid, Richard A. Lohsen, "Breakdown Criteria Due to Radio-Frequency Fields in Vacuum," Proc. 10th Int. Symp. on Discharges and Electrical Insulation, October 25-28, 1982, University of South Carolina, LA-UR-82-2400.

R. W. Warren, B. A. Newnam, J. G. Winston, W. E. Stein, L. M. Young, C. A. Brau, "Results of the Los Alamos Free-Electron Laser Experiment," submitted to IEEE Journal of Quantum Electronics, LA-UR-82-1811.