Food and Technology Division

Progress Report FY 1962

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The Accelerator Technology (AT) Division continued its mission in fiscal year (FY) 1992 to pursue science and technology and to develop new accelerator concepts for research, defense, energy, industry, and other areas of national interest. We had another successful year with significant accomplishments in the Ground Test Accelerator (GTA) program, the Free-Electron Laser (FEL) programs, the High Power Microwave (HPM) program and miscellaneous other accelerator related projects. Highlights for the year included the following:

- The 6th AT Division Advisory meeting, June 30-July 2, 1992, attended by Dr. Richard Briggs, SSC Laboratory; Prof. J. Mike Cornwall, UCLA; Dr. Robert Gluckstern, University Of Maryland; Dr. Hermann Gruner, CEBAF; and Dr. Crowley Milling, England; provided good support and feedback in our activities and new initiatives.
- AT Division, Medium Energy Physics (MP) Division, Los Alamos Neutron Scattering Center (LANSCE), and other organizations, participated in the initial studies for an upgraded LANSCE facility that would increase beam power to the target by at least an order of magnitude.
- All essential elements of the GTA accelerator have been tested successfully with beam acceleration—including injector, radio-frequency quadrupole (RFQ), matching, drift tube linac (DTL), controls, rf power, diagnostics, cryogenics, and beam design.
- The APEX facility and LANL staff continued to support the FEL program at Boeing with significant experiments and deliverables, including obtaining very bright beams through bends and small wiggler tubes, lasing at 837 nm, and operating with a photocathode-based electron injector.
- Accelerator-based spallation neutron sources received much more attention; a number of potential applications were highlighted and new initiatives were started. These include APT, ATW, ABC, a front end cw demonstrator, and a new LAMPF/LANSCE possibility for neutron-based science/technology studies.

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of scientific research and the timely initiation of participating in industry research and development efforts in power systems, control systems, and systems for the processing of chemical products, which include computer-aided design systems, and numerous related applications.

ANALYSTS, RFPs, and other information and data provided in the following sections are intended to provide a general overview of the current state of the art.

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Programmatically AT-Division's funding level declined about 14% for FY 1992.

As the chart on this page indicates, about 62% of the division was engaged in the GTA program. A strong effort in program development has continued to help diversify the division's activities. Security awareness was addressed using DOE and sponsor requirements. The AT Division Security Council keeps the division informed of new developments in security regarding education/awareness, visitors, and documentation. In July, efforts began to declassify much of GTA and the associated computing and physical security.

The DOE Tiger Team in late FY 1991 found no major problems in AT Division; however, valuable feedback on environment, safety, and health (ES&H) issues and conduct of operations was provided. The benefits of the inspection have resulted in an increased awareness of ES&H and more efficient ways to accomplish ES&H functions.

Tiger Team preparation and the formation of a directorate-based TA-53 ES&H support team resulted in enhanced communication and cooperation between AT and other organizations at TA-53. Collaborative efforts have addressed site access control, emergency preparedness, common training issues, and accelerator interlock standards.

The division has taken steps to maintain ES&H excellence in an environment of reduced funding. A formal self-assessment program, including quarterly inspections, was started and is coordinated by the division office; we are currently scheduling and coordinating ES&H training. We are also performing waste management and inspection activities to reduce building manager workload. These initiatives are intended to reduce overhead costs and allow groups to invest more time in programmatic work.

ES&H continues to be a high priority. Division operations were included in a Laboratory environmental compliance audit of TA-53. The GTA cryogenic cooling system passed important LANL and DOE safety reviews to allow acceptance testing with liquid hydrogen. A draft of the GTA Phase 2 (24 MeV) safety analysis report was completed and sent to HS Division for internal review. A safety review of the Advanced Free-Electron Laser (AFEL) was conducted before any hazardous operations at the facility. The AFEL environmental assessment (EA) was approved by DOE, and another EA was started for the planned Accelerator Prototype Laboratory.

Over 290 publications were entered in the AT Division Publications Data Base during FY 1992. In addition to the publications, assistance was provided for the production of many proposals, reports, manuals, and forms. The publications office also provided expertise in computer conversions, software advice, design and layout of newsletters, newswatches, graphs, charts, viewgraphs, and data bases.

In the following pages, we describe FY 1992 progress with summaries of our major programs and program development initiatives and group accomplishments. AT personnel had much to be proud of in their accomplishments.

I would like to take this opportunity to thank everyone in the division for their contributions, insights, and concerns and for sharing their many talents. Your efforts and your striving for success have made the division stronger and have allowed us to be responsive to our many sponsors. Thank you one and all.

S. O. Schriber

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Introduction

Rapid progress continued throughout this year with the following accomplishments. The GTA team procured and fabricated \$12M of hardware. The matching section between the radio-frequency quadrupole (RFQ) and the drift tube linac (DTL) was installed on the beamline. Beam was accelerated, steered, and bunched for the matching to the DTL during a commissioning period from February to April. The first of the DTL modules was installed, and in a second commissioning run from September to November, beam was accelerated and steered through the module. As a result of these commissioning runs, we have now integrated and tested all essential elements of the Ground Test Accelerator (GTA): ion source, low-energy beam transport (LEBT), RFQ, intermediate matching section (IMS), one DTL module, three 425-MHz tetrode amplifiers, one 850-MHz klystron modulator, and the associated diagnostics and controls.

We continued to fabricate, assemble, and test off-line the DTL modules in parallel with our effort to fabricate, assemble, and integrate the radio-frequency (rf) power system. Utilities such as instrumentation and control (I&C) and power wiring, water, air, vacuum, and cryogenic cooling were installed and made operational. The 40-kW liquid hydrogen cryo plant passed its acceptance test, and the GTA control room became fully operational.

Because of a funding decrease from \$50M to \$39M, we had to reduce GTA personnel from an average of 220 people in FY 1991 to an average of 150 people in FY 1992. Our industrial partnership with Grumman Aerospace continues successfully, with approxi-

mately 18 Grumman engineers and scientists participating in all areas of GTA. We also employed 25 engineers, designers, and technicians from a number of manpower contract houses.

Injector

As a result of an off-line development, we were able to replace the small angle ion source (SAS) with a new 4X source. This source was designed with a 4X larger cathode spacing that decreased the power density on the electrode surfaces. This replacement resulted in a very reliable operation and quieter currents of up to 65 mA with the expected design emittance. We have now accumulated about 3 000 hours of successful injector operation.

To reduce the previously observed emittance growth in the LEBT, we shortened the length of the LEBT in two steps. First, we eliminated the steerer coils and used the physical motion of the ion source and the repositioning of the RFQ's upstream end for beam "steering." Second, we incorporated Lambertson-type steering coils into the two solenoid lenses; steering with these coils was very satisfactory. The length of the LEBT was reduced by a factor of 2 from 150 cm to 75 cm, thus reducing the observed emittance. We achieved required matching at the RFQ entrance through optimization of two solenoid and two steerer currents.

In parallel with the operation of the 4X source, a 4X upgrade source was designed and fabricated. The improved features included a reduction of H_2 flow by a factor of 2 to 3, better mechanical tolerance for predictable precise dimensions after reassembly, and an enlarged cesium oven leading to

~ 300 hours of operation. The reduced H_2 gas flow lessens the need for pumping and thereby allows for a reduction in the length of the LEBT. Off-line tests of the 4X upgrade source are in progress.

Radio Frequency Quadrupole (RFQ)

The RFQ has operated very reliably with essentially no breakdowns during a succession of commissioning runs totaling ~ 1 000 hours. Reconditioning required very short times ranging from 0.5 min during operation to 5 min after a night without operation. Reconditioning after exposure to air takes approximately 1 hour.

The RFQ was thoroughly evaluated against its performance specification and the physics design during experiment 1B. To better understand the measured transmission we compared the original beam dynamics design with a new design that includes the effect of multipoles and image currents. This design has enabled us to understand the measured transmission.

Intertank Matching Section (IMS)

The IMS provides eight "knobs" to optimize the matching of the RFQ beam to the DTL entrance. Two cavities permit bunching, debunching, and acceleration. Four variable field quadrupole magnets provide for focusing and defocusing, and two quadrupole steering magnets permit steering and offsetting of the beam.

We had significant problems conditioning the IMS, particularly the convoluted coaxial feed line, because of multipactoring and electrical breakdowns. We solved the problem by reworking line details, heating a segment that ran in close proximity to the cold RFQ, and incorporating reflected rf power protection. The IMS and feed line are now reliable; however, reconditioning time remains longer for the IMS than for the RFQ.

The IMS was thoroughly evaluated during experiment 1C. We measured centroid steering, transverse and longitudinal emittance, phase scans, and transmission. When we modeled the beam transport for low-brightness currents, we discovered the fixed-focusing strength of the quadrupole steering magnets had to be reduced. This reduction will result in a more "robust" behavior of the IMS. We plan to grind the aperture of the steering magnets to reduce the field strength.

Drift Tube Linac (DTL)

The two main thrusts in the DTL area included installing and commissioning the first DTL module on the beamline (experiment 2A) and fabricating, assembling, and off-line testing modules 2-10.

The first module was fully assembled; drift tubes were aligned at room temperature, and the module was tuned at room temperature. This included tuning the cavity to 850 MHz and adjusting the couplers to achieve desired axial field distribution. We checked room temperature alignment and tune at the cryogenic operating temperature of 20 K in the low-power cryo test bed; DTL positioners were also exercised, and the position change of the DTL from room to cryo temperature was measured. Next, the module was conditioned up to 130% of the operating power at 20 K in the high-

power cryo test bed. All 10 DTL modules will undergo the same test sequence before installation on the beamline. A picture of 8 DTL modules in various stages of completion is shown in Fig. 1.1.

The first module was installed on the beamline in vacuum vessel #1 (the entire 24-MeV DTL will be housed in two vacuum vessels). It was fully integrated with diagnostics and controls and reconditioned *in situ*.

During experiment 2A, the first module was commissioned with the ion source, RFQ, and IMS, resulting in the most complete and successful GTA commissioning run thus far. The run demonstrated integrated operation of all elements of the 24-MeV accelerator. The purpose of experiment 2A was to characterize the beam and the operation of the structures, to verify the design, and to prepare for beam transmission and acceleration through all 10 DTL modules.

The operation of the 3.2-MeV accelerator (Fig. 1.2) was very reliable; all structures performed well. Reconditioning of the DTL module was rapid: 0.5 min without breaking the vacuum during operation, 10 min without breaking the vacuum overnight, and 1 hour after opening to air. The source delivered a very quiet, reliable beam. Vast amounts of data were compiled as a result of the wide variety of measure-

ments made on the following:

RFQ matching and steering
RFQ, IMS, and DTL transmission
DTL transverse emittance versus

- *macropulse time*
- *IMS variable field quadrupole times*
- *IMS buncher times*
- *DTL times*

DTL longitudinal emittance vs input energy
Beam centroids vs steering (DTL, IMS)
Phase scans vs power (DTL, IMS)
RF phase and amplitude control verification
Beam jitter
X-ray calibration of DTL power
Slit and collector vs microstrip probe steering measurements
Hybrid LINDA tests
Video profile tests

Radio Frequency (rf) Power

During the DTL commissioning run (experiment 2A), all elements of the rf power system were operated for the first time in an integrated mode. Three tetrode amplifiers provided reliable 425-MHz power to the RFQ (135 kW), to the first IMS cavity (6 kW), and to the second IMS cavity (12 kW). One 850-MHz dual-klystron modulator provided power for the first DTL module (60 kW) and the high-power conditioning stand. The system was very responsive to the daily needs of the commissioning team and worked reliably.

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Fig. 1.1. Drift tube linac module status (Juanita Romero, AT-4). Production line in full operation; five modules complete.

Fig. 1.2. The 3.2-MeV accelerator is being commissioned in the GTA tunnel (left, Darryl Sandoval and Ralph Garcia, AT-3).

The off-line testing of the 12 Thompson klystrons was completed successfully. The second modulator has been assembled and checked out on the mezzanine. The remaining modulators are in various stages of assembly (Fig. 1.3). The large capacitor bank used for creating the 2-ms pulse has been assembled and is ready for integration with the crowbar system and the 5-A high-voltage power supply. The low-level rf control system has been designed, and circuit board production for the prototype has begun.

Beam Diagnostics

All beam diagnostics necessary for diagnosing and controlling the beam have been integrated into the accelerator and thoroughly exercised. These include an automated emittance scanner used to measure beam emittance in the LEBT. Toroids, before and after the RFQ and the DTL, are used to measure beam current and transmission. Microstrip probes located in the IMS and on the diagnostic plate measure beam centroid position, angle, and energy. A video profile system after the IMS measures centroid profile and position. Two slit and collector

assemblies and three Faraday cups on the diagnostics plate complete the beam diagnostics for the 3.2-MeV accelerator.

The beam diagnostics worked well during experiment 2A, although questions remain regarding centroid position and angle measurements of the large aperture microstrip probes used on the diagnostics plate. Redesign of the beam tube for better continuity and symmetry of the return currents should correct this deficiency.

We developed and used successfully a fast-protect module based on the transmission loss through the RFQ and DTL, which is measured as a current difference. We also developed and performed off-line tests on a prototype beam-loss monitor based on γ -ray detection. These beam-loss monitors will be used throughout the accelerator at higher energies.

Controls

The controls systems (i.e., system software, application software, and the IOCs) have kept pace with the demands of the growing GTA facility. These systems exhibited good reliability

during the last commissioning run (experiment 2A) and enabled the commissioners to collect, archive, and retrieve data quickly and reliably. Several diagnostic processes such as emittance scanning and phase scanning have been automated. They work well and have reduced dramatically the time required for data acquisition.

Recently during experiment 2A, we introduced several new control functions and demonstrated them successfully. These include the fast-protect function, the alarm manager, and an adaptive feed-forward module that controls phase and amplitude fluctuations of the rf cavity power. The control room was made fully operational and is working satisfactorily.

Cryogenic Cooling Plant

A 40-kW liquid hydrogen plant was designed and built during the last 3 years. This plant uses liquid hydrogen as the primary coolant for a high-pressure gaseous helium loop that actually cools the accelerator cavities to 20 K. One of the most difficult and time consuming tasks involved preparing the Safety Analysis Report and receiving final approval from the health and safety organizations of the Laboratory and Department of Energy, which took 3 years and several man-years of effort to accomplish. Moreover, the cryogenic plant passed its acceptance test in May and is now fully operational. The 40-kW plant will be used to cool the entire 24-MeV accelerator in FY 1994.

We continue to employ the existing 700-W Koch refrigerator for all experiments with the existing beamline up to 3.2 MeV and for the high power conditioning of all DTL modules.

Optics

The GTA optics team continued to support the neutral particle beam space experiment (NPBSE) design effort led by Grumman. Several designs were produced.

The design for the ground based optics for GTA progressed successfully and culminated in a physics design for the high-energy beam transport (HEBT) section the 180° bend, and a conceptual physics design for the telescope. The key parameters for the optics design are

- 3.1-m diameter bend,
- 11-m long, 12.5-cm diameter telescope,
- 5th order aberration control, and
- 6 μ rad divergence.

The purpose of the HEBT is to match the DTL to the bend and provide for longitudinal expansion and beam steering into the bend, which is accomplished with four variable field permanent-magnet quadrupoles while providing for a dejitter cavity if necessary.

The bend's purpose is to demonstrate the feasibility of 180° bending of high-current beams with minimal emittance growth and beam loss. The bend accomplishes this with a triple achromat, each containing five cells with a defocusing, bending, and focusing

permanent magnet. The bend is designed to transmit currents up to 50 mA.

A major breakthrough was achieved during FY 1992. We developed a method to contour high-order field components to minimize the feed-up of geometric aberrations. The contoured high-order components were built into the permanent-magnet objectives by tailoring the radial and rotational positions of the permanent-magnet stacks. Electromagnetic corrector packages for second through sixth order correction permit the correction of effects due to geometrics, ambient fields, and space charge. By using this method, we can reduce the telescope length to 11 m. To minimize the cost of the new objectives, we will reuse the permanent magnets from the original 40-m telescope objectives.

Summary

FY 1992 was very exciting technically. It culminated with the 3.2-MeV commissioning run that demonstrated the integrated operation of all elements of the 24-MeV accelerator. The accelerator ran successfully during 3 weeks of experimentation, the beam current was quiet and stable, the rf power system delivered power reliably, and the cavities performed without electrical breakdowns. Our commissioning team will be busy for months evaluating the large amount of data acquired.

Our plans for FY 1993 are to install all 10 DTL modules into 2 large vacuum vessels over the waveguide basement. In parallel with this activity, we will complete the 5 dual-klystron modulators and build 1 preproduction low-level rf control system. Because of severe funding constraints, we will bring the optics designs only to the preliminary design review level without making any long-lead procurements.

Fig. 1.3. Bill North (left), John Bancroft, Bill Reass, and Glen Zimmerman prepare five high-power klystron modulators for operation.

Defense Free-Electron Lasers

Introduction

During 1992 the Los Alamos Defense Free-Electron Laser (FEL) Program continued to be teamed with Boeing Aerospace and Electronics in support of the Average Power Laser Experiment (APLE). The ultimate aim of the APLE program is to demonstrate that a FEL can produce laser light with an average power of 100 kW. A major Los Alamos contribution to this effort is the APLE Prototype EXperiment (APEX). The purpose of APEX is to demonstrate the basic physics and technology of APLE at low-duty factor. Following the 1991 commissioning of APEX, the 1992 effort focused on physics experiments associated with the FEL opera-

tion. Highlights included lasing at a wavelength of 837 nm, the shortest to date for a Los Alamos FEL. Ultrahigh current densities of 7000 A/cm² were demonstrated from the APEX photocathode, significantly exceeding the previously reported values for multialkali photocathodes. The electron beam's brightness at the end of the APEX 40-MeV accelerator was measured to be 3×10^{12} A/(m-rad)² at a current of 135 A making the APEX beam one of the world's brightest high-current electron beams. Single-bunch wakefield effects were measured directly for the first time using fast streak camera techniques, and a scheme for mitigating wakefield effects in a high-current accelerator was developed.

In addition to supporting the APLE program, the APEX facility was used to support a DOE-funded experiment that demonstrated the photolithography of semiconductor computer chips using a FEL beam. At the Boeing facility in Seattle, the joint Boeing/Los Alamos high-duty 5-MeV-photoinjector test stand achieved operation at 25% duty factor and an average electron-beam power of 160 kW. Such high-duty operation of a photoinjector was an important milestone on the road to the high-power FEL goal.

The APLE program involves many Los Alamos National Laboratory groups: APLE Project Office (program management), AT-7 (accelerator physics and APEX project leadership), CLS-6 (drive-laser and optical diagnostics), P-15 (electron beam diagnostics), MST-7 (photocathodes), X-1 (theory and simulation), AT-4 (mechanical engineering), AT-5 (rf controls), and AT-8 (automation).

Fig. 1.4. APEX beamline in September 1992, showing the oscillator wiggler region (Patrick Schafstall, AT-7).

Background

Funding for the Los Alamos Defense FEL Program is provided by the Strategic Defense Initiative Organization (SDIO) and the United States Army Strategic Defense Command (USASDC). Under the auspices of SDIO, a collaboration on FEL research was initiated between Los Alamos and the French Atomic Energy Commission FEL facility at Bruyère-le-Châtel near Paris. The French are in the process of commissioning a FEL driven by a radio-frequency (rf) photoinjector linac similar to that at APEX. During FY 1992, a number of mutually beneficial exchange visits were made to both FEL facilities.

Following the initial lasing of the APEX FEL in June 1991, we directed our efforts in FY 1992 toward characterizing the electron and optical beams with the goal of verifying the design codes used for the APLE FEL design. A secondary goal was to complete the APEX beamline through the 150-degree bend and FEL amplifier leg. A new effort was undertaken to bring the sections of the APEX beamline under automated computer control. These goals were achieved as planned.

Achievements

During FY 1992, the APEX linear accelerator operated in a hitherto unexplored regime of high current and high charge (>100 A at 1 nC) and low emittance ($< 5 \pi$ mm-mrad normalized, rms).¹ The 40-MeV linac has four separately driven tanks; the first is a 6 MeV on-axis coupled structure, and the remaining three are side coupled. All the structures operate in the $\pi/2$ mode at 1.3 GHz. The peak current is approximately 300 A in 15-ps full-width-at-half-maximum (FWHM) bunches. Individual bunches are separated by 46 ns. This bunch spacing is determined by the round trip time for the optical pulse in the FEL resonator. The FEL configuration used for our experiments was an oscillator with a near-concentric resonator and an

untapered permanent-magnet wiggler in the Halbach configuration.

Detailed descriptions of the APEX accelerator and FEL can be found in Refs. 2-5. Figure 1.4 shows the oscillator wiggler and adjacent sections of beamline.

Photoelectron Emission

The photocathode material used at APEX is CsK₃Sb driven by a frequency-doubled Nd:YLF laser.⁶ We chose this configuration because it produces high electron-beam current for modest drive-laser power. We studied the photoelectron current as a function of both drive-laser power density on the cathode and injection phase relative to the rf. Figure 1.5 shows the photoemission characteristic curves for our cathode. In generating these curves, we held the cathode's diameter at a constant 3 mm and the drive-laser pulse length at 10 ps. For each drive-laser power, we varied the injection phase and measured the charge extracted using a wall-current monitor immediately downstream from the

photoinjector, approximately 80 cm from the photocathode surface.

The electron current at the cathode surface is not measured directly. Because the electron emission from the cathode is prompt, the temporal length of the electron pulse near the cathode is less than or equal to the drive-laser pulse length. We measured the charge for each micropulse reaching the wall-current monitor. The current at the cathode is estimated by dividing the total charge per micropulse by the width of the drive-laser's FWHM pulse.

The variation of drive-laser phase and power have their analogs in thermionic cathodes. Phase is analogous to the cathode voltage, and power is analogous to cathode temperature. (Note that increasing the drive-laser power does not increase the emission energy of an electron; it increases only the number of electrons emitted.) Figure 1.5 illustrates the source-limited regime (low drive-laser power) and the space-charge-limited regime (high drive-laser power). At low drive-laser power, the

Fig. 1.5. Photoemission current density at the cathode vs drive-laser injection phase relative to rf, in the space-charge-limited regime (drive-laser power density ≈ 18 MW/cm²), and the source limited regime (drive-laser power density ≈ 1.3 MW/cm²). The cathode radius was 1.5 mm and the drive-laser pulse width was 10-ps FWHM.

curve makes the transition from space-charge-limited emission (0° to 20°) to the source-limited emission (flat top) and then back to space-charge limited again. This corresponds to the normal operating drive-laser power and current density at APEX.

At high drive-laser power (18 MW/cm^2 or $18 \text{ } \mu\text{J/cm}^2$ per micropulse), the emission is always in the space-charge-limited regime. In fact, we have observed current densities as high as 6800 A/cm^2 . The corresponding charge emitted per micropulse is 68 nC/cm^2 . For a nominal cathode diameter of 10 mm , an extracted charge of 50 nC per micropulse would be expected for the equivalent drive-laser power density. This regime is far from our normal operation. Because our accelerator is not designed to effectively transport such high charges and currents, we anticipate that significant emittance growth will occur. However, these results demonstrate the capability of photocathode systems to produce very high currents.

Emittance and Brightness

Following the photoinjector, the beam is accelerated to approximately 40 MeV by three side-coupled $\pi/2$ -standing wave structures referred to as tanks B, C, and D. Each tank is separately powered by a Thomson TH2095 klystron. Between each tank we have insertable view screens from which the electron-beam profiles are imaged using optical-transition radiation (OTR). Electron-beam micropulse current is determined from wall-current-charge monitors and OTR streak-camera micropulse measurements.

Emittance is measured at the end of the linac using the quadrupole-scan technique. The emittance numbers quoted here are normalized root-mean-square values. Figure 1.6 shows the emittance as a function of micropulse current measured at an electron-beam energy of 36 MeV . The numbers plotted are the geometric mean of two orthogonal measurements averaged

over 440 micropulses. The predicted curve is generated using the code PARMELA, the primary beam-dynamics code used for electron-linac design at Los Alamos.

The *unnormalized* emittance at 135 A is $0.046 \pi \text{ mm-mrad}$, which is sufficient for FEL lasing at wavelengths as short as 160 nm . The measurement of such low emittances at high charge and current from a photoinjector linac verifies the solenoidal emittance compensation scheme proposed by Carlsten.²

Figure 1.4 shows the corresponding normalized rms brightness as a function of current. The brightness is defined as

$$B = 2I/\epsilon^2,$$

where I is the micropulse current and ϵ is the rms emittance. The factor of π in the definition of emittance is explicitly used to determine the brightness. The maximum brightness observed to date is $3 \times 10^{13} \text{ A/(m-rad)}^2$, at a current of 135 A and an electron-beam energy of 36 MeV . The energy spread, which was averaged over 220 micropulses, was measured at $0.24\% \text{ FWHM}$. This measurement compares with a PARMELA prediction of 0.15% for a single micropulse.

Transverse Wakefields

We have paid particular attention to mechanisms that degrade the emittance and brightness of the electron beam. During FY 1992, we focused on the effects of transverse wakefields in the linac. Because of dipole rf fields in the side-coupled accelerator tanks, transverse kicks are experienced in the electron beam that induce head-to-tail transverse-wakefield kicks in the micropulse and hence result in emittance growth. The trajectory required to minimize the wakefields is not intuitively obvious to the accelerator operator. To assist in determining the optimum trajectory, we installed our streak camera to monitor the electron micropulse temporal and spatial profile on a screen located at the end of tank D. Consequently, we were able to directly observe the effects of the wakefields on the electron beam as shown in Fig. 1.7. The operator can easily choose a trajectory that minimizes the wakefields and optimizes the emittance. A detailed knowledge of the optimum trajectory is not required. The degree of emittance degradation resulting from wakefields is shown in Fig. 1.6. In this figure, the PARMELA curve without wakefields corresponds to the emittance when the electron beam is steered to minimize wakefield effects. The PARMELA curve with wakefields corresponds to the electron beam when it is steered to center on the screens between each accelerator tank.

Fig. 1.6. Electron beam rms normalized emittance vs micropulse current.

FEL Performance

The detailed specifications of the APEX FEL resonator and wigglers are given in Ref. 5. Typically, lasing has been at wavelengths near $3\ \mu\text{m}$. The 6.9-m resonator is an asymmetric, near-concentric design. The asymmetry results from placing the optical waist at the wiggler center, which is 0.5 m upstream from the resonator's geometric center. The resonator mirrors are coated with a multilayer dielectric to reflect greater than 99% at $3.0\ \mu\text{m}$. A small fraction of light, which is transmitted through the optic, is transported to a diagnostic table located within 5 m of the out-coupler. Sensors on this table allow for characterization of the small-signal gain, cavity loss, energy, spectral content, spatial intensity distribution, and temporal intensity evolution.

The resonator mirrors tend to suffer coating damage when the macropulse-average intracavity mirror flux is high. Consequently, the macropulses are kept short (20-40 μs), and the charge is kept low (1 nC). During the lasing described below, the electron-beam micropulse is usually 10-ps FWHM, with a macropulse energy spread of less than 0.5% and a normalized rms emittance of approximately $4\ \pi\ \text{mm-mrad}$. Simulations with the above configura-

Fig. 1.7. Electron beam rms normalized brightness at 36 MeV vs micropulse current. The estimated brightness from our previous accelerator with thermionic injector and 20-MeV energy is shown for comparison.

tion and operating parameters have been performed using the FELEX code.⁸ This small-signal gain predicted by FELEX is approximately 200%. Our experimental measurements show gains in excess of 160%. The start up of the optical macropulse is shown in Fig. 1.8. We have found the small-signal gain measurements difficult to perform. FELEX simulations show that the gain is large for only a small number of micropulses (approximately 10 micropulses or 0.5 μs) at the start of the macropulse. Furthermore, rf transients

at the start of the macropulse can make the initial lasing unstable.

Fig. 1.8. Direct observation of transverse wakefield kicks on electron micropulses (a) head-to-tail kick removed by optimum choice of steering, (b) head-to-tail kick evident. Transverse wakefield effects of the micropulse are measured directly using a streak camera and OTR screen; these data are for a current of 290A, pulse width of 14 ps.

When the FEL is lasing at wavelengths near 3 μm , very strong sidebands are evident (Fig. 1.9). Such strong sidebands would reduce the efficiency of a high-extraction FEL with a tapered wiggler. Recently, we directed our efforts toward the study of sideband suppression techniques. The first suppression technique we attempted was the introduction of Brewster plates into the resonator cavity.⁵ We found that these plates strongly suppress the sidebands. The suppression occurs at all plate angles including Brewster's angle. At Brewster's angle the insertion loss of the plates is approximately 0.5% per pass. We believe that the suppression occurs because the Brewster plates act as a dispersive element. The first sideband is displaced by approximately 3% in wavelength from the fundamental. Dispersion in the plates results in a round trip path-length change of 17 μm relative to the fundamental. Previously we showed that detuning a cavity without Brewster plates by approximately 10 μm was sufficient to suppress sidebands. However, detuning the cavity also results in a reduction in the gain on the fundamental. The Brewster plates allow the detuning of the cavity for the sidebands while maintaining cavity synchronism on the fundamental.

We have begun collaborating with Mission Research Corporation to test a new method of sideband suppression. This technique involves using a phase-

step mirror as a replacement for one of our regular resonator mirrors.^{9,10} We believe the phase-step mirror technique will be more applicable to high-average power FEL applications than the Brewster plate technique.

Short-Wavelength Lasing

During FY 1992, approximately 25% of APEX effort was devoted to a DOE-funded program to develop ultraviolet FELs for photolithography of semiconductor computer chips. The goal of the proof-of-principle experiment at APEX^{11,12} was to show the modestly sized FEL could be used to produce ultraviolet light (250 nm). As part of this effort, we have begun harmonic lasing with both our existing permanent-magnet wigglers and a new electromagnet microwiggler. By the end of FY 1992, we had lased at wavelengths down to 827 nm with a permanent-magnet wiggler. Using the microwiggler, we observed spontaneous light emission at wavelengths close to 500 nm.

Automation

The APEX control room was originally designed and constructed in the early 1980s. All controls were manual with no computer intervention. In 1992 we received funds from USASDC for the purpose of developing computer controls and automation for subsystems of APEX. As a basis for our control system, we chose the Experimental

Physics and Industrial Control System (EPICS) control architecture developed for the Ground Test Accelerator as part of the Neutral Particle Beam program. By the end of FY 1992, we had converted all the beamline magnets to computer control. An automated method of measuring the electron-beam emittance was implemented using the quadrupole-scan technique. Automation of the drive-laser was considered to be one of the more intractable problems. A major breakthrough was a method developed to determine the phase of the drive-laser micropulses relative to the rf phase of the accelerator. Using this method, we were able to implement automated feed-forward control on the drive-laser phase that gave long-term stability of less than 2 ps. In addition, the drive-laser micropulse temporal width was also brought under automatic control. The pulse width is now controlled at 10 ps with a jitter of less than 0.5 ps. These techniques eliminated many of the manual adjustments previously required to maintain the drive-laser in stable operation. Control of the electron current from the photoinjector was automated by developing a feed-forward loop between a current monitor and a drive-laser power attenuator.

Future Plans

Continued contraction of the national defense FEL program resulted in a funding reduction for the Los Alamos program. In July of 1992, a partial termination notice was received from USASDC, which will result in the elimination of the APEX experimental program and the FEL theory effort in FY 1993. The remaining Los Alamos effort in defense FELs will be in direct APLE support in the areas of photocathode drive-lasers, electron beam diagnostics, and low-level rf controls. APEX will continue to operate for part of FY 1993. The main effort will be to support the photolithography program by pushing the lasing wavelength to smaller values with the ultimate goal of 250 nm.

Fig. 1.9. Start up of lasing at 3 μm , showing a small-signal gain of 160% per pass. The individual micropulses are 46 ns apart.

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1992 Status Report for AXY Programs

Potential applications of high-power accelerator-driven spallation neutron sources expanded dramatically during 1992. The Department of Energy (DOE) funded an 18-month design study of Accelerator Production of Tritium (APT), the National Academy of Sciences reviewed Accelerator Transmutation of Waste (ATW), and a Laboratory-Industry collaboration put forward a proposal to study Accelerator Based Conversion (ABC) of Russian weapons plutonium. A Los Alamos proposal was also submitted to the Defense Nuclear Agency (DNA) for building the first stage of a high-power continuous-wave (cw) proton linac front end to demonstrate key aspects of the technology. The steadily increasing number of programs are now referred to collectively as AXY, where the A stands for high-power accelerator, and the remaining letters represent the specific application.

Considerable progress was made in developing accelerator conceptual designs, in identifying and addressing key technical issues for high-power cw linacs, and in examining important design questions, such as mechanisms for the generation of beam halos. A 1-week workshop on high-power accelerators and spallation targets was held in November between Los Alamos designers and colleagues from ITEP and MRTI in Moscow and from other institutes in Russia.

APT Program

Following the successful outcome of a JASON panel review of Los Alamos and Brookhaven proposals for Accelerator Production of Tritium in January, the DOE decided to fund an 18-month

study of the concept. The study was structured as a collaboration between Los Alamos National Laboratory (LANL), Brookhaven National Laboratory (BNL), Sandia National Laboratory (SNL), and was initially managed by the New Production (NP) office of DOE. NP's purpose is to provide APT input to the Programmatic Environmental Impact Statement (PEIS) for Complex 21 and to assess the technical feasibility and costs of the APT concept. LANL is responsible for the APT accelerator design and for a target/blanket and processing system based on converting the tritium decay product ^3He back into tritium. BNL is responsible for a target/blanket system similar to the one presented to the Energy Research Advisory Board (ERAB) in 1989, based on a matrix of lead and LiAl rods. SNL is responsible for the environmental, safety, and health evaluation of the APT design and specifically for coordinating the PEIS input. The APT study is fleshed out by contracts with industry for engineering support, costing, and A/E services to define the Balance of Plant (BOP).

With the closure of the NP office of DOE at the end of 1992, the APT program is to be transferred to the Defense Programs (DP) office.

Accelerator Design

The APT linac reference design calls for a 1-GeV, 200-mA cw proton linac. The high-energy-beam transport serves one of two alternate production target/blanket assemblies, with a specification of 75% overall plant availability. The linac architecture pictured in Fig. 1.10 consists of a funneled front end that combines 100-mA beams from two 20-MeV 350-MHz linacs, followed by two 700-MHz high-energy accelerating structures that provide a 1-GeV, 200-mA output. Each of the low energy linacs consists of a 75-keV proton injector, a 3-MeV radiofrequency quadrupole (RFQ), and a conventional drift-tube linac (DTL). The accelerating structure following the funnel is a short-tank bridge-coupled drift tube linac (BCDTL) that contains no quadrupole magnets in the drift tubes. The final accelerating structure, which is about 850-m long, is a coupled-cavity linac (CCL) in which each 14-cell tank is driven by a single high-power klystron. A key feature of the high-energy structures is a large aperture-to-beam-size ratio in order to meet the very low beam loss requirements needed for

Fig. 1.10. APT accelerator concept: 1000-MeV, 200-mA cw proton linac.

ensuring hands-on maintenance. Short tanks and a quadrupole doublet focusing scheme help in the attainment of this objective. A low accelerating gradient (1.25 MV/m, average) in the CCL provides high rf efficiency and minimizes life-cycle costs.

A high-energy beam transport (HEBT) system conveys the protons from the end of the linac to one of two alternate tritium production target/blanket assemblies. While one of these assemblies is in production, the other can be serviced. The transport system consists of a doublet focusing lattice matched to that of the linac, followed by an achromatic bend, and terminating in an expander based on nonlinear optical elements. The expander converts the small-size nearly Gaussian beam distribution from the accelerator into a large area uniform density distribution at the target face.

Program Events

The APT program received a status review in September 1992 of the reference design. Key PEIS input data, such as estimated radioactive air releases, are to be provided to Sandia by the end of January 1993. A comprehensive review of the complete APT system design, including PEIS impacts, is scheduled for early March 1993. A set of topical reports on the design of all aspects of APT, with participation by industrial partners, will constitute the final FY 1993 program deliverable.

ATW Program

The Laboratory is continuing to study Accelerator Transmutation of Waste (ATW). The initial application of this scheme was focused on destruction of the accumulated high-level radioactive wastes at the DOE's defense production sites, principally at Hanford, but this year the study emphasis has shifted to include transmutation of spent commercial power reactor fuel. The base line ATW system being considered incorporates a 1600-MeV, 250-mA cw proton linac that drives four high-ther-

mal-flux neutron sources surrounded by D₂O blankets in which the materials to be transmuted flow in aqueous-based carrier loops. This system could transmute the actinide and fission product waste of about eight 1-GWe light water reactors, converting it to stable or shorter-lived products that do not require deep geologic storage. A more advanced high-temperature ATW system, based on a helium-cooled graphite blanket with molten salt carrier loops, is also being examined. It promises higher electrical efficiencies, and opens up the possibility of accelerator driven subcritical fission systems that could convert fertile material to fissile fuel, burn the fuel to produce energy, and transmute all long-lived nuclear waste generated in the process.

DOE Environmental Restoration and Waste Management (EM) funds have supported chemistry and material balance studies for ATW, while accelerator and target/blanket design have been supported by LANL-directed research and development (LDRD) dollars. Key activities this year have revolved around a comprehensive review of separations technology and transmutation systems (STATS) for high-level nuclear waste. This review is being conducted for the DOE by a special panel of the National Academy of Sciences. The ATW accelerator design was reviewed by the STATS panel transmutation subpanel in April as part of a complete review of the Los Alamos ATW schemes.

ABC Proposal

In FY 1992 an industry-led consortium, with Los Alamos as a major partner, proposed to study a special ATW system dedicated to converting returned Russian weapons plutonium. The proposal, led by Grumman Aerospace Corporation (GAC), is aimed at funds made available by the 1992 Nunn-Lugar legislation dealing with US assistance to Russia in dismantling nuclear weapons that have been eliminated in recent stockpile reduction agreements. The proposal is for a study

that would develop a reference design for an Accelerator Based Conversion (ABC) system that would be built in Russia as a joint US/Russian technical project. The study would also assess the feasibility of implementing an Integrated Test Facility (ITF) for prototyping the ABC process at an upgraded version of LAMPF. Several interactions between LANL, US industrial participants, and relevant Russian scientific institutes and government agencies took place throughout the year, culminating in a Moscow workshop on target design and chemistry for ATW/ABC systems and a Los Alamos workshop on ATW/ABC accelerator design. Both workshops were held in November 1992.

DNA Proposal

Los Alamos also submitted a proposal for funding to the DNA for developing a high-power cw accelerator front end that is generic to ATW, ABC, and APT applications and that also has application to a future LAMPF front end replacement. Accelerating structure frequencies have been chosen to match those of LAMPF. Thus, if the initial program can be extended into a 4- to 5-year program, it will be possible to develop a complete demonstration of the front-end cw accelerator technology for transmutation systems. The hardware would then be converted into the first stage of a LAMPF accelerator upgrade suitable both for driving a recently proposed advanced spallation neutron research facility (LANSCE II) as well as an ITF that could evaluate ATW technologies. The proposal to DNA includes an assessment to determine what is necessary to upgrade the LAMPF linac's power level for ATW technology and to implement the new technology in demonstration facilities. The proposal also includes a study of the intense pulse provided by the Proton Storage Ring (PSR) for weapons effects measurements.

A new initiative is under study by a Los Alamos National Laboratory (LANL) interdivisional team, with strong AT participation. This large project would greatly increase the capabilities of US neutron scattering facilities, including the Los Alamos Neutron Scattering Center (LANSCE). LANSCE now provides the world's most intense burst of neutrons for research in a wide range of condensed-matter topics and biological studies. A nominally 1-ms H⁻ macropulse from the Clinton P. Anderson Meson Physics Facility (LAMPF) containing some 3×10^{13} particles is accumulated for about 2500 turns in the Proton Storage Ring (PSR) and is then delivered to a refractory metal target in a 200-ns burst to produce the desired spallation neutron pulse. The net beam power to the target approaches 80 kW. A rival source, ISIS, operates at the Rutherford Laboratory in the United Kingdom, and other smaller spallation sources throughout the world accommodate a large community of neutron scattering workers. Such pulsed-spallation sources provide a much higher peak neutron intensity (though less average intensity) than do nuclear reactors designed for neutron research. Hence, although reactors are useful to neutron scattering work, they lack the pulsed character essential to much of the research.

Recent interest has arisen regarding sources of substantially greater neutron intensity than that of LANSCE. The European community has undertaken a 2-year study for a 5-MW spallation source that would exceed existing reactor average intensity. Discussions within Los Alamos this spring provided impetus for a similar proposal from the Laboratory. In particular, funding for LAMPF as a nuclear physics facility is scheduled to end with FY 1993.

Hence, the conversion of LAMPF to a high-power neutron-source driver is very attractive, both in preserving the present facility and in meeting national research goals. Additionally, reusable parts of the linac and the extensive infrastructure built up over the past 25 years would substantially lower the construction cost and effort of such a spallation source over a "green-field" facility. The notion of emphasis on neutrons at Los Alamos is not new; several years ago AT personnel, in a study known as LANTERN, suggested that the future of the mesa was in neutron production and advocated this direction for several purposes, including waste transmutation, defense applications, and energy production as well as neutron scattering. Most of the recommendations of that study are now under active pursuit by the Laboratory.

In August 1992, a site visit by the Department of Energy's Basic Energy Sciences Advisory Committee (BESAC) provided us with the opportunity to present our proposal. A conceptual design for a 5-MW facility had been proposed internally and was quickly augmented with technical detail as well as a preliminary cost analysis. Presentations were made by AT, LANSCE, and Medium Energy Physics (MP) personnel to the committee. Shortly thereafter, a Los Alamos contingent was invited to a workshop in Chicago, held in conjunction with the BESAC committee site visit to Argonne National Laboratory, to present our proposal to the BESAC accelerator subcommittee. Again, a crash effort was mounted that led to a more detailed design and cost assessment. The presentation went smoothly and appeared to be well received, thanks to a great deal of effort by numerous individuals in the Division.¹

The proposal noted that LAMPF is currently a 1-MW facility with a very reliable coupled-cavity linac (CCL) section that comprises over 90% of the linac. The proposal includes replacing the present 200-MHz front end with a 400-MHz radio-frequency quadrupole (RFQ) drift tube linac (DTL) combination, both to increase reliability and to provide an upgrade path to even higher power. The beam (at 20 MeV) then enters a new 800-MHz DTL for acceleration to 100 MeV and matching to the present CCL. This arrangement enables funneling at the 20-MeV level for an upgrade to 5 MW of beam power as shown in Fig 1.11. No upgrade of the CCL rf power is required in the 1-MW case because the linac presently carries current at this level (at 120 Hz) and hence provides the same average power. Additionally, by doubling the front-end frequency, the charge per bunch is actually reduced from the present LAMPF operating conditions.

We designed an accumulator ring with achromatic bends and a 140-m-circumference "race-track" configuration for the 1-MW case. The achromatic bends promote a high degree of linearity that is undisturbed by chromaticity corrections. Injection is accomplished by single-stage foil stripping and phase-space painting is planned. There are many issues in the required accumulation of over 10^{14} particles in the ring (several times that successfully accumulated in the PSR). We will draw heavily on the lessons learned in the PSR studies to increase storage capability. Beam losses and the electron-proton instability are particular issues encountered in the PSR to which we must pay close attention. Because of the increased ring size, the resistive-wall instability, unimportant in the PSR, will dominate and active damping will be required. A sophisticated rf system using several harmonics will also be required to keep the beam longitudinally confined to provide an extraction gap. When we include the sophisticated bump system for injection painting and an extraction kicker, it is clear that the ring requires extensive pulsed-power implementation.

Fig 1.11. Upgrade path for LANSCE II. The 1-MW case is shown at the top. In a 5-MW scenario, a funnel at the 800-MHz DTL is completed and the rf power throughout is doubled.

After one-turn extraction from the ring, the highly compressed beam pulse is conducted to two target stations, where neutrons are produced by beam impingement on a refractory metal target. The neutrons interact with energy-moderating materials and then pass through holes in the shielding surrounding the target for use in a wide variety of instruments. The LANSCE staff will now study the high-intensity target design and develop plans for a research facility.

The upgrade to 5 MW would require doubling the rf power throughout the linac and increasing ion-source intensity to 100 mA as well as completing the funnel at 20 MeV. Two additional rings would be required for sequential accumulation; storage in each would be increased by almost 70%. The parameters of this upgrade are very stressing and we must prove that they are attainable. The major issues identified so far include

- chopping the beam on a 1-ms time scale to leave a gap for extraction in the ring,
- current carrying ability of the CCL,
- ring stability and storage time,
- system reliability, and
- system particle losses and activation.

Some of these issues lead us to conclude that a higher energy (up to 2 GeV) would be helpful because the current needed to produce the required power is decreased and ring stability is enhanced. Such an option would require either an afterburner linac or replacement of the CCL. In either case, a superconducting linac provides an attractive option.

We expect to have a preliminary design proposal ready for August 1993, which would position us for possible construction funding in 1996. Our initial estimates for the 1-MW-scenario construction cost are over \$500 million; the planned upgrade would cost an additional \$340 million.

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JAERI OMEGA Project and Intense Neutron Source for Materials Testing

JAERI OMEGA Project

The Japan Atomic Energy Research Institute (JAERI) continues its OMEGA Program activities in the evaluation of new options for disposing of radioactive waste, and again provided funds to AT-Division to explore system layout and optimization for the 1600 MeV, 10-30 mA cw linac required and to pursue studies of beam loss control.

This year's report included a collection of memos on AT-Division point-design activities for accelerators of this class as they would be applied to radwaste transmutation or tritium production. The AECL Research Company was subtasked to contribute their ideas on the ion source and low-beta accelerator components.¹ The report continues with a discussion from AT-4 on manufacturing process and cost models for a high-beta coupled-cavity linac (CCL) and its subsystems, in which thermal frequency shifts, vacuum, and electromagnet quadrupole considerations are highlighted. The two concluding chapters are new work on the space-charge physics architecture of CCLs in the 350-700 MHz frequency range and scaling and optimization studies of these long linacs. The point designs were evaluated in terms of total beam size along the accelerator, and preliminary criteria were developed for making some of the many choices required for optimization.

Intense Neutron Sources for Materials Testing

Work for the DOE/Office of Fusion Energy (OFE) continued during FY 1992 as the materials community laid the groundwork for making an international proposal. Meetings of the international community reaffirmed the candidacy of the D-Li (deuteron bombarding a lithium target) as the near-term technology of choice. The US effort was organized under an ad-hoc committee chaired by Oak Ridge National Laboratory (ORNL), to begin preparing material for making an international proposal around the end of FY93. Functions and requirements documents, issue outlines, and R&D requirements documents were prepared for an IFMIF scale facility, requiring a 35-40 MeV cw deuteron linac at up to 250 mA cw current.

In parallel, the JAERI Energy Selective Neutron Irradiation Test (ESNIT) facility proposal effort continues. This facility would use a 50-100 mA deuteron linac for fusion and basic materials research and may form part of a staged international effort. JAERI provided funds to AT Division for conceptual design studies directed to the ESNIT requirements. Our work for the first report included design of a beam-redistribution system that uses nonlinear magnetic elements to produce a rectangular beam spot on target that is nearly uniform within the rectangle and drops cleanly to very low levels outside. Initial work on optimization of a room-temperature RFQ and drift tube linac was completed, and theoretical development included consideration of a normal-form analysis of the anharmonic oscillator model and a contraction mapping scheme for finding matched three dimensional envelopes.

A major new consideration in accelerator technology for an IFMIF was proposed to the community — by the time IFMIF construction might begin, superconducting (SC) accelerator cavities might be the preferred technology in technical and cost terms, if a thorough R&D program was supported before final commitment to an SC approach was made. At present, SC rf cavities and magnets are being used in many new accelerator installations and are beginning to prove their reliability and cost effectiveness. The very high-intensity machines under consideration in AT Division add another dimension; because high-intensity ion beams have not been run in SC linacs, very low beam-loss is a key issue, and the machines must run very reliably in a factory environment with many operating hours per year. Considerable work is required first to develop the required components, including cavities, rf power couplers, instrumentation, crystats, etc., then to demonstrate the components with a high-power ion-beam and operate them reliably for some period. The philosophy and procedures for maintenance also need to be thoroughly developed. However, there are good technical reasons why SC cavities might be advantageous in terms of larger apertures for beam-loss minimization, and higher accelerating gradients for shorter length. In combination with possible savings in capital and especially operating costs, we have committed ourselves to a thorough evaluation of the SC possibility.

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Introduction

The Advanced Free-Electron Laser Initiative (AFELI) is funded to support high-quality basic and applied research in the field of Advanced Free-Electron Lasers (AFELs) and to demonstrate these advanced technologies. AFEL research will provide an understanding of the performance and engineering limits of free-electron laser (FEL) systems, thereby strengthening the science and technology base for existing and future Laboratory and national FEL initiatives. The goal is to build a second-generation FEL system to research and develop advanced components. This system will incorporate state-of-the-art components and be friendly and robust. Research and developmental areas include the various subsystems of the FEL: the electron source, accelerator, wiggler magnet array, optical system, diagnostics, and control system. State-of-the-art components include ultrabright, high-gradient, low-loss accelerators; electromagnetic microwigglers; emittance-preserving magnetic bunchers; and advanced optical resonators. This second generation of FELs, referred to as compact FELs because of their size, has many potential applications in industry, medicine, and research.

Fig. 1.12. Permanent magnet wiggler.

Description

The present design of the compact FEL consists of a high-brightness accelerator and a microwiggler. The electron source is a laser-driven photoemitter that produces 2-nC and 10-ps-long micropulses at a rate of 108 MHz. The macropulse is 20 μ s long and has a rate of 10 Hz. The electron beam is accelerated to 20 MeV by a 1.2 m on-axis coupled structure operating at 1300 MHz with a field gradient of 22 MV/m. The accelerated beam has excellent beam quality with a transverse emittance of less than 3 -mm-mrad and an energy spread of 0.3%.

Two types of wigglers will be used: a permanent magnet wiggler and a pulsed-current wiggler. The permanent magnet wiggler (Fig. 1.12) has 24 1-cm periods. The peak magnetic field is 0.4T on-axis. The pulsed-current microwiggler (Fig. 1.13) is 10-cm long with a 3-mm period and has a slotted tube design. It is driven by a pulsed dc

current of 10 kA to generate a magnetic field up to 5T on-axis. The length of the optical resonator is 1.4 m. Including operation at higher harmonics, the laser wavelength extends from 7 μ m down to 0.4 μ m.

Fig. 1.13. Pulsed-current microwiggler.

The experiment will use the control system developed by AT-8. This control system will be used initially for monitoring system parameters. Later in the program, the control system will be used for active control.

Fig. 1.14. Brazed copper linac structure for the advanced FEL linac.

Fig. 1.15. AFEL electron beamline.

The FEL facility is at Meson Physics Facility, Technical Area 53, building 14. The accelerator and FEL are so compact that they can be housed in a 12 ft x 25 ft vault.

The accelerator structure has been fabricated (Fig. 1.14), and schematic of the AFEL experiment is shown in Fig. 1.15. The beamline, shown in Fig. 1.16, consists of permanent magnet quadrupoles and dipoles; permanent magnet elements are used to improve reliability and compactness. The permanent magnet wiggler has been constructed, and the pulsed tube wiggler is under construction. The first beam was obtained in June of 1992; the first FEL operation is expected in the spring of 1993.

Fig. 1.16. Carl Timmer (background) and Steven Kong (postdoctoral fellows) work on the AFEL. The accelerator is in the background; the electron beamline with FEL optics are on the optical table in the foreground.

During 1992, several groups in AT Division were involved in providing support to the Superconducting Super Collider (SSC) Laboratory near Dallas. These activities are summarized here and covered in more detail in the specific groups involved.

In the SSC linac area, AT-1 has designed, fabricated, and delivered a 4-vane, 2.5-Mev, 428-MHz radio-frequency quadrupole (RFQ) to SSC. AT-5 fabricated a tetrode amplifier for this RFQ, which SSC has coupled to and successfully tested on the RFQ. AT-1 has continued to provide support in the cavity design for the 1284-MHz coupled-cavity linac. Additionally, AT-1 provides beam-simulation support to the SSC Linac Group on an as-needed basis. AT-3 is modifying the design of some adjustable-gradient permanent-magnet quadrupoles developed for the Ground Test Accelerator (GTA) that will be used in the SSC RFQ-to-drift tube linac (DTL) matching section. These quadrupoles are very compact in comparison to equivalent electromagnet designs. In the low-level rf area, AT-5 continues to work closely with the SSC rf group to provide a low-level rf control system, using development work done for GTA.

In the low-energy booster (LEB), AT-7 has carried out beam-dynamics calculations to better predict and control the effects of beam loading in the rf cavities. AT-5 collaborated with SSC in the design of the perpendicular-biased ferrite-loaded rf cavities that must swing from 47.5 to 60 MHz in 50 msec at a 10-Hz repetition rate. AT-1 is also providing rf-cavity design support. AT-3 and AT-5 provided modeling support in the design of the 10-Hz resonant-circuit ring magnet system. AT-3 is consulting with the Accelerator Diagnostics Department on the diagnostics design. Similar support in all these areas is being provided for the two other booster rings.

In the collider rings, AT-3 provided support in the prediction of the transmission-line modes in the long strings of superconducting magnets. Because the superconducting magnets form a nearly lossless transmission line, power supply ripple can propagate long distances with little attenuation and lead to emittance growth. AT-3 has proposed a way to damp these traveling waves and limit the magnetic field ripple to less than 1 part in 10^9 .

In the accelerator controls area, SSC critically evaluated several control systems, both commercial and in use at other national laboratories, and selected the AT-8-designed Experimental Physics and Industrial Control System (EPICS) to be the baseline control system for use on all accelerator systems at SSC. EPICS is also being used in the GEM detector collaboration.

The High-Power Microwave (HPM) Program

AT Division maintains a program management and program development effort in high-power microwaves (HPM) on behalf of all organizations at the Laboratory with expertise applicable to that technology. Laboratory-wide program management of HPM is resident in AT Division because of the substantial concentration of the expertise in the division. Other divisions currently involved are A, CLS, IT, M, MEE, MST, P and X. This section presents an overview of that effort, which is described in detail under AT-9 activity since virtually all division work in this area is conducted in that group.

It has been recognized from the earliest days of radio that electromagnetic radiation (EMR) at rf wavelengths has potential as a weapon. Although technology did not effectively support this application of EMR until recently because of limitations on rf power at appropriate wavelengths, it has now become feasible to use EMR to disrupt or destroy military electronics at useful ranges. Vulnerability considerations have shown that the appropriate wavelengths are in the microwave regime. Various agencies of the Department of Defense (DoD) have active programs to develop HPM weapons. The Laboratory and division have participated for a number of years because of the unique capabilities here and because of potential synergism with accelerator applications within the Laboratory mission, as noted below.

The DoD has long been concerned about the accidental adverse effect of HPM on military systems, such as that aboard modern naval ships where nearby systems can interfere with one another. With the growing possibility of *intentional* interference or destruction by a microwave weapon, this concern has multiplied and resulted in extensive programs to understand the vulnerability of US military systems to HPM. A related interest in HPM effects resulted in funding by the Department of Energy (DOE) and its predecessor agencies as well as the DoD because of the importance of the "electromagnetic pulse" from nuclear weapons. Again because of the availability of unique rf sources, instrumentation, and facilities, the Laboratory and division have for many years participated in these vulnerability programs.

Future generations of high-performance rf accelerators will require amounts of rf power well beyond that available through a reasonable number of current technology sources. Thus, a strong source-development effort is an important part of the nation's rf accelerator program. Work on advanced sources for this application has also been an important part of the division's past HPM activity.

The main thrusts of HPM program development have been to participate actively in national HPM program management and to detect and pursue opportunities to apply the division's unique capabilities to HPM problems of national importance. HPM program management is intended to ensure effective technical and financial execution of programs, once funded, and to conduct sponsor liaison. To learn about the technical work performed in this area, the reader is invited to review the section of this report that covers Group AT-9.

Neutral Particle Beam (NPB) Power Systems Highlights

During calendar year 1992, work has continued in the Accelerator Technology Division on the Directed Energy Weapon Power Integration (DEWPOINT) power program.

Unfortunately, a substantial decrease in program funding caused a reduction in the number of technologies that could be pursued.

In the original DEWPOINT program, there was a dual path for all critical technologies. It was planned to pursue two sources for rf power: the klystron, a vacuum tube composed of gridded tube input structure and klystron output structure, and a solid-state amplifier. Similarly, two sources of prime power were also being pursued. The hyperconducting alternator was the primary thrust with the lithium-thionyl-chloride battery being the backup for short mission times.

Because of the funding cuts, the program was reduced to solid state amplifier development with a hyperconducting alternator as the prime power source. An ambitious program was undertaken to develop a hybrid amplifier module (HAM) at 850 MHz. The output power from this module is designed to be 1 kW and the module weight is estimated at 90 g. The HAM is to be the basic building block for a 500 kW amplifier. Each HAM would have 16 solid-state triode (SST) chips. The solid-state triode is an FET-type device with V-I characteristics much like the curves of the vacuum tube.

The HAM, shown in Fig. 1-17, has outer dimensions of approximately 4.25 x 2.5 x .25 inches, which include the input splitter circuitry and the output combiner circuitry as well as the heat sink. It can be appreciated that the power density in this module is high, which places a severe burden on the

cooling scheme. The cooling scheme chosen was developed at Lawrence Livermore National Laboratory and is called a microchannel heat sink. The transistor chip is bonded to an aluminum nitride substrate, which is, in turn, bonded to a silicon microchannel heat sink. The heat sink has many narrow grooves through which the coolant passes. The cooling capability is greatly enhanced because the fins created by the cutting process greatly increase the cooling area and the width of the channels are less than the laminar layer thickness of the fluid passing through them.

Testing of the initial HAM is scheduled for the spring of 1993 with final HAM testing scheduled for the summer.

Successful operation of the hyperconducting alternator requires high purity aluminum wire. This wire

has been developed by ALCOA and they have achieved a purity of 99.9995%. When operated at 20 K, the wire has characteristics similar to a superconductor without the troublesome problem of quenching. By using high purity aluminum wire in the construction of the alternator, not only is wire weight saved, but losses are greatly reduced, which decreases the cooling requirement. All these things reduce the size of the alternator. The current estimated specific weight of an alternator using this technology is less than 0.1 kg/kW.

ALCOA has successfully fabricated 800 feet of rectangular high purity wire; the wire is 0.16 in. square. Because high purity aluminum is very soft, the wire undergoes an involved fabrication process that includes being drawn. This requires the wire to be clad with a shell of Al-Fe-Ce for strength. There are many potential applications for this technology in transformer and rotating machinery design where superconducting characteristics are desirable. One need not use hydrogen for cooling; either neon or helium might be used.

Fig. 1-17. Hybrid amplifier module.

Over the past years, rapid and extensive changes in global politics have clearly indicated that weapons research is no longer a top national priority. National security and well-being are now more dominated by issues of economic competitiveness. These changes have caused AT Division to recast its business strategy so that greater breadth is added to the previously concentrated focus on accelerator-based advanced weapons systems. Examples of such programs are the Strategic Defense Initiative Organization (SDIO) support for missile defense systems using neutral particle beam (NPB) and free-electron laser (FEL). An opportunity to broaden our market for accelerator technologies has occurred through the Department of Energy's (DOE) and Defense Programs' sponsored Technology Transfer Initiative (TTI). This TTI was created as a "dual-benefit" program whereby the DOE supports Laboratory development projects that have aligned industrial support (i. e., the industry supports its own personnel and facilities with "in-kind" resources project development activity). The dual-benefit realized is (1) industry is the beneficial recipient of the Laboratory's advanced technologies and competencies with the goal of becoming more competitive in the high-technology marketplace, and (2) the Laboratory is the beneficial recipient of transitional financial support allowing for development of new technology markets. Although the most visible, TTI is not the only avenue available by which to pursue industrial partnering. Additionally with the change in governmental administration, there will assuredly be increased incentive for the Laboratory to engage in industrial partnering as a way to strengthen economic competitiveness. This was reflected in the Laboratory Director's definition of industrial partnering as a strategic thrust area that is projected to grow to 20% of the Laboratory's budget.

During FY 1992, AT Division began transitioning some of its projects to be more aligned with the commercial and industrial sector. Examples of such activities and identification of the relevant industrial partners follow.

EPICS: The Experimental Physics and Industrial Control System (EPICS) developed by AT-8 has been united with Titan Industries and Tate Systems. They will adapt the EPICS software package to control problems in the commercial marketplace.

Klystron Microwave Tube Development: AT-5 joined with Varian Industries to commercially develop high-power, high-efficiency microwave klystrons for the communications marketplace (e. g., high-definition TV broadcasting). Clearly the benefit to AT Division is a less costly microwave power source manufactured in the United States for future accelerator projects (e. g., Accelerator Transmutation of Waste [ATW] and Accelerator Production of Tritium [APT]).

Low-Level Radio-frequency (rf) Controls: AT-5 has also found an industrial partner, Kinetic Systems, to market its low-level rf control units.

Electron Beam-Plasma XUV Source: Grumman Electronic Systems and Etec Systems, Inc., have joined with AT-7 to develop a unique extreme ultraviolet or soft x-ray (XUV) source with applications to semiconductor lithography.

Microwaves for Chemical Processing: DuPont has paired with AT-9 to develop high-power microwave systems that facilitate chemical processing either by bulk heating or by inducing catalytic reactions.

Low-Energy Proton Accelerator Systems for Medical Applications: AT-1 has united with Neutron Technologies and more recently with Babcock and Wilcox to develop Boron Neutron Capture Therapy. Similar ties may also be created to develop commercial systems for proton therapy.

Frequency Agile and Compact FEL Systems: We are identifying programs to develop such FEL systems with Grumman Corporation as the industrial partner. The most noteworthy application for such a system is in naval ship defense in which the sensors of incoming cruise missiles will be defeated.

Permanent-Magnet and Soft-Magnetic Material Development: AT-3, with Applied Materials Corporation, has proposed to develop advanced magnetic materials for use in accelerator structures and controls.

Plasma Processing Systems for Ion Implantation: AT-5 will supply the modulator and microwave systems needed by General Motors to develop ion-implantation on large volume and irregular surface objects (e. g., car engine blocks).

Accelerator Based Conversion: This most ambitious program development has as its industrial partners Grumman, Westinghouse, and Bechtel Corporation. The activity involves marketing accelerator systems similar in performance to APT, but whose function is to drive a neutron source that converts weapons plutonium or other fissile material into a nonweapons grade isotope. An upgrade of such an accelerator based conversion (ABC) system could even "burn" the fissile material to produce energy.

The formation of these industrial partnerships does not guarantee that all will receive DOE funding. However, we expect the number of AT-Division ties with industry for the purpose of commercializing accelerator technologies to increase in the coming years.

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Introduction

The AT-1 Group, Accelerator Physics and Special Projects, provides accelerator design and physics support for various AT Division projects. The staff at AT-1 also pursues advanced topics in accelerator physics and technology. Additionally, AT-1 builds small accelerators for special applications. What follows is a summary of the various AT-1 activities for the 1992 fiscal year.

Accelerator Projects

Ground Test Accelerator Project Support

The design of low-energy and high-energy end walls for the ten Ground Test Accelerator (GTA) drift tube linac (DTL) tanks was completed during FY 1990. These end walls are cryogenically cooled, brazed-copper units. The end walls for tanks five through eight were fabricated and tested during FY 1991. The remaining two units were completed during FY 1992.

Photoinjector Linac for the Advanced Free-Electron Laser (AFEL)

Under funding for the Experimental Research and Development Initiative and in conjunction with AT-7, we completed a 1300-MHz, 20-MeV photoinjector linac for the Advanced Free Electron Laser (AFEL). This unit (Figs. 2.1 and 2.2) is now in laboratory service. In many ways, the AFEL linac is similar to both the 6-MeV high brightness accelerator FEL (HIBAF) (FY 1989, now APLE prototype experiment [APEX]) and the 6-MeV National Center for Laser Research (NCLR) (University of Twente, FY 1991) photoinjector electron linacs. Like them, it is a compact, brazed-copper, on-axis, coupled, radio frequency (rf) structure. It employs the same photocathode hardware as APEX,

so that they may eventually share photocathode production and transport systems.

The AFEL linac differs from its two predecessors primarily in final energy (20 MeV, 11 accelerating cells versus 6 MeV, 6 accelerating cells) and in its capability for cryogenic operation. The system can be cooled with either liquid nitrogen or water. The copper rf structure is thermally isolated from its surrounding vacuum vessel, allowing *in situ* rf baking to achieve the high vacuum ($<1 \times 10^{-9}$ torr) required by the cesiated photocathode. At temperatures approaching 77K, the electrical resistance of the copper is expected to be significantly lower than at conventional operating temperatures, producing a quality factor (Q) enhancement of

about 2. In addition, the thermal expansion coefficient is lower and the thermal conductivity higher at those temperatures. These three factors contribute to the possibility of a much higher rf duty factor than is otherwise possible without direct nose cooling. More subtle improvements have been made in the form of larger focusing and bucking solenoids and in the number and orientation of the coupling slots that connect the accelerating cavities to the on-axis coupling cavities. These improvements are expected to result in the brightest electron beam source yet.

The photoinjector linac was delivered in FY 1992 and has been operating at ambient temperature. Tests of cryogenic operation are planned for FY 1993.

Fig. 2.1. Schematic of 1300-MHz, 20-MeV cryogenic linac for the AFEL.

Fig. 2.2. Brazed copper, on-axis, coupled linac for the AFEL.

Radio-Frequency Quadrupole Linac for the Superconducting Super Collider

The 2.5-MeV, 428-MHz radio-frequency quadrupole (RFQ) for the injector of the Superconducting Super Collider (SSC) facility was delivered to the SSC Laboratory during the summer of 1992. The RFQ (Figs. 2.3 and 2.4) is a two-segment, continuous-cavity structure 2.2 meters long. Each segment consists of four vane/cavity quadrants joined by electroforming. This is the technique developed for the Beam Experiment Aboard a Rocket (BEAR) RFQ and was also utilized for the Continuous-Wave Deuterium Demonstrator (CWDD) RFQ. It was manufactured jointly by LANL and GAR Electroformers of Danbury, CT.

Side-Coupled Linac for the SSC

We are carrying out the detail mechanical design for the side-coupled linac (SCL) (Fig. 2.5) for the SSC. It is a 1284-MHz structure consisting of nine modules, each with eight accelerating tanks (72 total) joined by bridge couplers (63 total). This is a graded- β structure and will be described on 1400 mechanical drawings. The drawings are being produced by a CAD programming technique that allows the physics dimensions of the accelerator and bridge tanks to be read from data files so that the detail and assembly drawings can then be generated. This method will provide considerable savings in cost and time. The SCL will be a brazed-copper structure, fabricated in the Peoples' Republic of China.

Fig. 2.3. Schematic of the 2.5-MeV, 428-MHz radio-frequency quadrupole (RFQ) linac for the superconducting super collider (SSC).

Fig. 2.4. Final assembly of 2.5-MeV, 428-MHz RFQ linac for the SSC (front-left: Dale Schrage, Lloyd Young, Phillip Roybal, Felix Martinez, Angela Naranjo; rear-left: William Clark, Roy DePaula, Jim Billen, Doug Aikin).

Low-Power Tuning of DTL Cavities for the GTA

We have tuned the first five of ten 850-MHz DTL cavities for the GTA. Tuning included low-power measurements of the following: ramped field distribution, field stability, cavity Q, and coupling to the rf power source. Before post couplers were installed, the unstabilized field distributions agreed with predictions based upon SUPERFISH code calculations and applications for the Slater perturbation theorem. We adjusted and stabilized the relative field distributions to within $\pm 0.25\%$ of the design ramp. The low-power measurements also included the Q enhancement and the field distribution at cryogenic temperatures. There were no significant changes in the relative field distribution at cryogenic temperature. The room-temperature Q was typically 75% to 85% of the SUPERFISH Q, and the cryogenic Q was about 3.2 times the room-temperature Q.

Radio Frequency Measurement and Analysis Codes

We have developed a comprehensive collection of computer codes for measuring, analyzing, and displaying

field distributions in rf cavities. Development work began in 1984 for 8086-based computers. The codes now run on 486 and 386 PCs and include extensive on-line documentation. The programs BEADPULL and QUADPULL collect frequency shifts as a metal or dielectric bead traverses a resonant cavity at constant speed. QUADPULL measures fields in all four quadrants of RFQ cavities. Analysis codes apply the Slater perturbation theory to convert frequency shifts to fields. BEADPLOT plots the field distributions and calculates field integrals. DTLPLOT analyzes and plots the results of axial BEADPULL measurements in DTLs or coupled-cavity linacs (CCL). QUADPLOT does the same for QUADPULL data in RFQs. Supporting programs such as BEADPLOT, DTLPLOT, and QUADPLOT prepare design data for comparison with the measurements and compute averages of multiple measurements. Program COUPLING extends the accuracy of an impedance analyzer for Q and voltage standing wave ratio (VSWR) measurements. The COUPLING code plots reflection coefficients on a Smith chart and analyzes the resonance circle to get β .

Beam Dynamics

Effects of rf Transients in the CCL for the SSC

Each module of the CCL for the SSC consists of 8 tanks with 16 accelerating cells each. The tanks are coupled with bridge couplers. The rf power drive is in the center of the module at the bridge coupler between the fourth and fifth tanks. In simulations of the beam dynamics, the rf power is turned on 10 μ s before the beam is turned on. This time lapse allows the fields to build up and stabilize before they are required by the beam. When the beam is turned on, the beam loading causes the fields to change. This transient state of the fields, together with their effect on the beam was studied. We developed a model to calculate the field distribution throughout the module as a function of time. We then ran beam dynamics simulations with the results of this model corresponding to different times during the macro-pulse, deriving an estimate of the effect of the transients from the results of these simulations.

The code TRAN6 calculates the field amplitude and phase of all the accelerating cells versus time. TRAN6 displays a moving picture of the amplitude of all the accelerating cells, a history of the forward power, the average amplitude of all the accelerating cells, and the reflected power. The amplitude of each accelerating cell and coupling cell is shown by the small asterisks. The scale for the amplitude is shown on the left side of the plots, and the scale for the forward and reflected power is on the right side. The time scale is on the top of the plots. The scale on the bottom shows the accelerating cell number for the plot of amplitude versus accelerating cell number at the current time, which is displayed at the top.

Fig. 2.5. Mechanical design for the side-coupled linac (SCL) for the SSC.

In Fig. 2.6 the time has advanced to 10.75 μ s. The beam was turned on at 10 μ s. The amplitude in the tanks has dropped 1% to 2%. The rf power has increased because the feedback system is requiring more power to compensate for the beam loading. The rf power scale on the right side of the plot means percent of maximum klystron power. The simulation had proportional, integral, and differential (PID) feedback built into the code. This PID feedback on the rf power simulates a nearly ideal PID feedback control system; however, no feedforward that may be used on the SSC-CCL rf control system is included.

For beam dynamics simulation, we renormalize the design values E_d of the accelerating electric field in any given tank by the ratio of the transient field amplitude levels E_t in the tanks, and the steady-state values of E_s just before $t = 10 \mu$ s. The beam loading is assumed to be 12%, an average for the nine modules for a beam current of 25 mA. In the simulation illustrated by Figs. 2.6 and 2.7, we ignored the very small field amplitude tilt from cell to cell within a tank and took the average value as the field amplitude for the entire tank. Particle simulation runs were made for 1000 macroparticles transported through the entire CCL at several t values, before and after $t = 10 \mu$ s. Figure 2.7 shows the energy profiles at $t = 9.95$, 10.5, 10.75, 11.00, and 12.00 μ s, respectively.

As expected, the size of the transverse root-mean-square (rms) beam (not shown) during the transient stage does not change when compared with the steady state situation. However, the transient fluctuation in E_z causes phase-energy oscillations in the longitudinal phase-space, as shown in Fig. 2.7. The mean energy W_0 of the output distribution deviates significantly from the steady-state value within the first microsecond after $t = 10.0 \mu$ s. At $t = 10.75 \mu$ s, the mean energy deviation is 559 keV. At $t = 11.50 \mu$ s the conditions are virtually the steady state situation. No particles are lost at any

Fig. 2.6. TRAN6 display at time = 10.75 μ s.

Fig. 2.7. Energy profile vs tank number at (a) $t = 9.95 \mu$ s, (b) $t = 10.5 \mu$ s, (c) $t = 10.75 \mu$ s, (d) $t = 11.0 \mu$ s and (e) $t = 12.0 \mu$ s.

time because of the transient effect. There is also no statistically meaningful emittance growth during the transient stage. The deviation in the Phase is not significant.

Design and Simulation of a Bridge-Coupled DTL for Accelerator Transmutation of Waste

Recent Los Alamos designs of high-current, continuous wave (cw), proton linacs for accelerator transmutation of waste (ATW) incorporate beam funneling to achieve desired levels of current, emittance, and rf efficiency in the high-beta accelerating structure. Typical designs have a front end consisting of two 350-MHz linacs, each composed of an RFQ and a DTL, which accelerate protons to 20 MeV. The two beams are funneled into a 700-MHz CCL that has a final energy in the range of 800 to 1600 MeV. The design choice for a 700-MHz accelerating structure in the 20 to 80 MeV region would conventionally be an Alvarez DTL with permanent-magnet quadrupoles (PMQs) in the drift tubes. However, for high-current cw applications, the threat of radiation damage from beam loss makes the use of PMQs undesirable, and 700-MHz drift tubes cannot accommodate electromagnet quadrupoles (EMQs). The initial design approach was to begin the 700-MHz CCL structure at 20 MeV. Recent engineering analysis has shown that fabrication of such a structure at low-beta values would be complicated and power efficiency would be low. We have derived a modified DTL concept, the bridge-coupled DTL (BCDTL), that provides an attractive solution for the problem region, with simpler fabrication and higher efficiency. Figure 2.8 shows a schematic diagram of an ATW-type machine. The funneling energy is set at 20 MeV because of increased engineering complexity; stricter beam dynamics requirements at higher energies, i.e., higher deflector fields and increased number of funnel components; and the desire to minimize beam-loss-induced activation at the transition region. The

ratio of transverse aperture to rms beam size has been used as a figure of merit in estimating beam losses. In order to minimize beam loss, we have required this ratio to be 6 or larger above 20 MeV throughout the linac. This condition requires adequate transverse focusing throughout the linac to maintain beam size and to minimize emittance growth, which could produce beam halo. The ratio of aperture to rms beam size is dependent on the intertank spacing and the type of focusing lattice used. The number of accelerating cells per tank of the

BCDTL and the transverse phase-advance per focusing period were chosen to optimize the transverse ratio of aperture to rms beam size.

Using a modified version of the PARMILA code, the BCDTL shown in Fig. 2.9 was simulated from 20 to 80 MeV as 86 individual tanks with intertank quadrupoles for transverse focusing. In this situation there is essentially no transverse emittance growth. The longitudinal emittance, however, grows because of the constant accelerating gradient. This

Fig. 2.8 Schematic diagram of an ATW-type accelerator. The BCDTL would be used to accelerate the beam from 20 to 80 MeV after the beam has left the funnel.

20-MeV Bridge Coupled Drift-Tube Linac Module (700MHz)

Weight: Approx 3000kg
Power: 1.08 megawatts
Coolant flow: 100 gal/min

Fig. 2.9. Conceptual engineering drawing of what a four-tank module of the BCDTL might look like.

constant accelerating gradient allows the longitudinal focusing per unit length to become weaker as a function of distance along the linac. Nonetheless, there appears to be no effect of longitudinal emittance growth on the transverse emittance. Such an emittance growth could result in a degradation of the ratio of the aperture to rms beam size.

The results of this study indicate that the BCDTL could be a practical alternative to a CCL for the 20- to 100-MeV energy region of an ATW accelerator. This type of structure provides adequate transverse focusing of high-current beams as needed to control beam-loss-induced structure activation and is electrically efficient in this beta regime.

Superconducting Strong-Focusing RFQ

Our objective is to develop a niobium, superconducting, RFQ particle accelerator for high-field operation. This development would enable us to build very compact low-velocity rf ion linacs with energies up to about 10 MeV for protons and with the capability for accelerating high-beam currents. The project represents a new application for rf superconducting accelerators.

Our approach is to (1) determine the best parameter choices for the design of high-field superconducting proton RFQs; (2) identify the superconducting RFQ applications that appear to be most attractive, especially those that represent a good entry point for a phased development of the technology; (3) design and construct a prototype superconducting 4-vane cavity, and operate it at the highest fields possible; and (4) increase our understanding of the beam physics of high-current RFQ accelerators in order to enable us to take maximum advantage of the new technology we are developing.

Progress during the past year includes (1) RFQ beam-dynamics design studies that include the design, using a new

procedure, of an 11-MeV RFQ for radioisotope production for positron-emission tomography (PET); (2) completion of the cavity design for the 30-cm long niobium prototype cavity; (3) establishment of the mechanical design (Fig. 2.10) for the prototype cavity; (4) fabrication of the niobium cavity parts and stainless-steel fixtures for an electron-beam weld test; and (5) basic beam-physics studies, including measurements and analysis of the output beam from the world's highest-intensity RFQ at the European Center for Nuclear Research.

RFQ Linear Accelerator for PET Isotope Production

We have developed a new concept for a compact 11-MeV linear accelerator in a single 3-m RFQ structure. This new concept should be an attractive choice for a radioisotope-production accelerator for the PET application. We have investigated two options: (1) a normal-conducting copper RFQ, that would operate in a pulsed mode and (2) a superconducting RFQ that would operate in a continuous (100% duty factor) mode. The design concept includes a new approach, based on the recent RFQ that was built for the SSC application, that uses a ramped voltage to maintain high accelerating fields throughout the structure. This results in a very compact accelerator. Beam-dynamics calculations for an unoptimized design demonstrate the

basic feasibility of the idea. We are also fortunate that, at this frequency, the rf power sources are commercially available for both the normal and superconducting cases. The next step would be to produce an optimized design and build a prototype accelerator to demonstrate the concept.

POISSON/SUPERFISH Code Development for PC Compatibles

We have adapted the POISSON/SUPERFISH codes to run on 486 or 386 PCs. The PC version includes features not found in the standard version. These extra features include (1) control programs for automatically tuning RFQ, DTL, and CCL cavities; (2) a complex version of the rf field solver FISH; (3) memory allocation for temporary arrays; (4) many line regions for dividing the mesh into fine or coarse sections; (5) full support for multiple-cell DTL cavities; (6) plot files for displaying resonance-search and transit-time data; and (7) on-line documentation. We modified AUTOMESH extensively to generate self-consistent logical and physical coordinates. This new, more-robust code greatly reduces the number of crashes in LATTICE crashes that previously were caused by ill-formed mesh triangles along boundaries. Program FISH detects and corrects potentially poor placement of the driving point. Programs AUTOMESH, LATTICE, FISH, POISSON, SFO,

Fig. 2.10. The superconducting RFQ cavity prototype.

and VGAPLOT return DOS exit-error codes for use by control programs. The DOS exit-error codes solve arbitrarily large problems, limited only by computer resources. Each program allows free format entry of CON array elements, and provides error checking of the user entries. Our new root finder and convergence criteria have been implemented in release 4 of the standard version. We distribute the PC version of these codes to users in the accelerator community upon request.

Structures Development Laboratory

Cavity Development Activities

At the structures laboratory we concentrate on superconducting accelerator cavity development. This effort is directed at developing the database and technical expertise required to design a superconducting proton accelerator. Earlier work had identified pion acceleration as a programmatic goal. Changes in programmatic emphasis have given top priority to proton acceleration. All of the previous design and database work can be applied to the proton goal.

The design frequency of the accelerating structure matches the Los Alamos Meson Physics Facility (LAMPF) frequency of 805 MHz. In Previous fiscal years we concentrated our work on smaller 3-GHz cavities in order to establish an initial database and develop cost-effective handling techniques. This fiscal year we concentrated on testing single-cell 805-MHz cavities. We have achieved average and maximum values for peak surface electric fields of 30 MV/m and 50 MV/m, respectively. These are world class results, exceeding previously reported results at this frequency. The values are consistent with the design goals for the program, namely, a cavity average of 20 MV/m for the surface electric field. A next major step in the program is a test of a seven-cell, 805-MHz-cavity structure, complete with a stiffening structure for reducing microphonics, and a tuning fixture. The cavity (Fig. 2.11) was designed in FY 1992 and has been ordered.

The advantage of using superconducting technology for accelerator structures is amplified as the accelerating electric fields and the rf Qs ($Q = \text{rf stored energy/dissipated energy per cycle}$) are increased. Carefully controlled acid etching and cleaning of the niobium cells are essential if high fields are to be obtained. At Los Alamos the cells are acid-treated using facilities in MST division. The cells are then transported to AT-1's clean room for processing with ultraclean water. It is essential that ultraclean techniques are followed in the cleaning and handling of the cell. The cavity assemblies are sealed before they are removed from the clean room and subsequently inserted into the liquid helium cryostats (Fig. 2.12).

Vacuum-oven treatment may be required to prevent the so-called "European Q disease." The treatment removes hydrogen from the niobium that can form a hydride during relatively long cool-down times. The presence of the hydride can result in a

Fig. 2.11. Prototype design drawing for a superconducting seven-cell cavity for ion acceleration, emphasizing a mechanically rigid structure to reduce microphonics, field flatness upon cooldown to 5%, and high accelerating gradients.

Fig. 2.12. After clean-room assembly, an 805-MHz cavity is ready for testing in 2K helium superfluid liquid. (RB92 044 03)

degradation in the Q of the cell. The "disease" has been cured by heat treatment at 800°C.

If rf Q values consistently equal to or greater than the design value of 5×10^9 are to be obtained, the rf surface resistance of the niobium must be low and the thermal conductivity high. A high thermal conductivity reduces the likelihood of the occurrence of a quench at high electric/magnetic fields. Annealing the niobium in a high-temperature vacuum oven is effective in increasing the achieved values for Q s if the annealing also includes a process that removes oxygen entrapped in the niobium. This is done by titanium gettering in a vacuum oven at ~1500°C. Smaller 3-GHz cavities can be heat-treated with ovens in the structures laboratory. An oven large enough for a complete seven-cell structure is available to us through another division of the Laboratory.

Under certain conditions high-pulse-power (HPP) conditioning of a cell has improved the achievable electric field in a below-par cell. HPP is attractive because it offers an opportunity to recondition an accelerating structure without removing it from the cryostat. The testing reported here was done at

3 GHz. We still need to verify the results at 805 MHz.

Achievements

We developed sufficient database and expertise to allow us to advance beyond 3-GHz cavities and concentrate on 805-MHz-cavity processing and testing. We have achieved approximately a factor of 50% improvement in peak surface field over the previously reported results from the worldwide database at 805 MHz (Fig. 2.13). The average value of the achieved electric field, including an extrapolation to the seven-cell cavity, exceeds the goal for proton acceleration by ~10%.

During the fabrication of the seven-cell structure, niobium half-cells must be e-beam-welded together. However, welding reduces the thermal conductivity at the weld region. The cell is then prone to quenches from the superconducting state quenches that start at the equator weld, a region of relatively high current density. The fabricator can relieve this problem by heat-treating the entire seven-cell structure after welding. However, in our case, none of the potential fabricators had an oven large enough for the entire seven-cell structure. That situation required

us to seek a different solution. The iris region of the cell is a region of relatively low-current density; it is, therefore, less sensitive to quenching. We devised a fabrication procedure that allowed the fabricator to weld the half-cells at the equator, heat treat the resultant single cell, and assemble the seven-cell structure by welding the individual cells together at the iris. As a test of this procedure, niobium samples were welded together; some samples were then titanium-gettered heat treated. Comparison of the residual resistance ratio at 4K (RRR) values of the heat-treated and nonheat-treated samples showed that the damage to the RRR from e-beam welding could be repaired by the titanium-gettered heat treatment. We successfully tested the procedure using a 3-GHz cell.

This work, combined with additional analyses of structural vibration and mechanical stress, has allowed us to proceed with the next major programmatic step, namely the procurement of a seven-cell structure for tests in the vertical cryostat.

A higher-capacity, roots-type, helium vacuum pump was installed. This pump allowed us to achieve 2°K with 805-MHz cavities for the first time. Also, the time to reach 2°K with 3-GHz cavities was reduced from ~7 hours; an entire run can now be completed in a few hours.

A high-pressure (1000 psi) ultrapure water rinse was installed this fiscal year in the structures laboratory's clean room (Fig. 2.14). The water rinse has demonstrated its capability for removing particulates down to 0.5 microns in size. This unit is effective in removing dirt from complicated structures such as the welded bellows attachments to the cavity ports, and it was used in the achievement of the record value of 50 MV/m for the 805-MHz cavity.

Fig. 2.13. A collection of representative peak surface electric fields obtained in superconducting cavities by various laboratories throughout the world.

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Fig. 2.14. A technician readies a cavity for rinsing with 1500 psi ultrapure water. Cavity cleaning and assembly takes place in a class 10 (static) clean room by highly trained personnel. Contamination control technology is also evaluated in this area using airborne and liquidborne particle counters.

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Fig. 2.15. As part of building accelerator systems, components such as vacuum windows, cavity couplers, drivelines, and probes need to be characterized and matched before they are installed on accelerator cavities. AT Division has extensive experience designing and building these components. Shown is a VSWR measurement used for matching a coaxial elbow with a support stub.

The klystrons in the two COMARK transmitter modules are now operating at 805 MHz. The units previously operated at 500 MHz. We now have 10-kW cw capability and 100-kW pulsed capability at 805 MHz. These units can now be used to high-power-process cavities. Programmatic advantages accrue because we have demonstrated that cavities can be reconditioned *in situ*, thereby allowing us to return a faulty cavity to the line without having to return to room temperature for reconditioning.

Waveguide components (variable coupler, window, and supports) for the high-power test and the seven-cell test have been designed and prototype-tested and are now undergoing final fabrication in preparation for the HPP test and the seven-cell cavity test (Fig. 2.15). In addition, the vertical cryostat for the test of the seven-cell structure has been delivered to the Laboratory.

The main program thrust is directed at completing the preparations for and the test of the seven-cell structure in its vertical cryostat. Preparations include digging a pit in the high bay area of MPF-17 for the vertical cryostat. The program will also complete the HPP test of a single cell 805-MHz cavity.

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Introduction

The AT-3 group charter is to "apply beam transport theory, state-of-the-art diagnostic instrumentation, and advanced magnet fabrication and measurement techniques to the design, construction, and commissioning of magnetic optic systems." To fulfill its mission, the group maintains experimental and construction facilities that include a diagnostic laboratory, which fabricates beam-diagnostic electronics; a magnet-measurement laboratory, which performs precision measurements on a wide variety of electromagnets and permanent magnet assemblies; a mechanical design, fabrication, and assembly section; two rooms for laser development, used on the laser induced neutralization diagnostics approach (LINDA) measurement system for the Ground Test Accelerator (GTA); and an area in the high bay, which assembles beamlines. The group is also responsible for managing a staff machine shop located in MPF-18 that houses small lathes, milling machines, grinders, sanders, drill presses, a bead blaster, a bandsaw, a welding and brazing facility, and full vacuum leak checking capabilities.

Background

Our group employs 33 full-time employees: 12 technicians, 20 staff members, and 1 group secretary (aided by a part-time assistant). In addition, we have one industrial staff partner from Grumman Aerospace Corporation (GAC) and two contract employees.

Achievements

Optics Section

In FY 1992 the Optics Section continued to develop those capabilities necessary to study and design beamlines and output optics systems that must meet very demanding requirements. We also created designs and conducted studies that support a variety of Los Alamos projects.

New Techniques and Code Development

In a collaborative effort with J. van Zeits at the University of Maryland, we developed computer codes to calculate higher order aberrations, now making it possible to fully optimize high-order aberration coefficients. These results have been checked against numerical integration and other codes developed at GAC that are not capable of optimization. Consequently, a significant development, the concept of contoured-field telescopes, was developed. The principle is that the longitudinal dependence of each multipole is determined by the requirement that, while constrained to serve its primary function, it also does the least damage to the next higher order of aberration. This technique generates designs in which the residual high-order aberrations are reduced by one or two orders of magnitude. Consequently, we have been able to apply this work to the GTA and the neutral particle beam space experiment (NPBSE).

We have studied various first-order achromatic 180° bend designs, including space-charge effects. We developed the ACHRO code to help us quickly generate and evaluate designs for new requirements. This work has been applied to the GTA Optics Experiments design.

We refined our nonlinear beam redistribution method and created designs for several projects described below. Our designs take the beam leaving an accelerator and generate a distribution that is, to a good approximation, uniform over a large rectangular region on the target.

We verified some aspects of Parmila emittance growth predictions caused by quadrupole roll errors in linacs. In this work, we used P. Channell's mismatch-emittance-growth theory to estimate emittance growth in terms of the roll-angle error.

We continued to develop the TRACE3D code, which is used

frequently for the first-order beamline design. We ported the code to UNICOS, replacing the previous CTSS version for the Cray. We also completed an implementation for SUN workstations, in which we wrote a replacement for the PLOT10 library, eliminating the need for a Tektronix terminal or emulator. This implementation uses the same TRACE3D code used on VAX VMS systems, eliminating the need to maintain separate SUN and VAX versions.

We continued to develop the BEDLAM code, an experimental three-dimensional, high-order space-charge code that represents a beam by the moments of its phase-space distribution. We tested the space-charge algorithm and verified that the moment approach, as expected, works very well in generating beams that are matched to high order in the presence of nonlinear forces.

Beamline Designs and Project Support

We completed a new design of the GTA high-energy beam transport (HEBT) that includes an insertable beam dump. Variable field permanent magnet quadrupoles (PMQs) expand the beam in the beam-dump mode.

We designed a 3.1-m bend for GTA, which consists of three five-cell, first-order achromats. This design was studied extensively to determine effects of various magnet and beam errors and to determine the aperture and steering requirements.

We determined that an energy-corrector cavity is required for GTA only if the energy errors are beyond a certain value, that a bunch rotator is not needed, and that we need a two-frequency (425 and 850 MHz) momentum compaction system at the end of the bend. The system requirements were determined using a newly developed specialized code that computed the fraction of beam on a distant target, using an actual telescope design to estimate chromatic effects.

The measured beam behavior in the intermediate matching section (IMS) of GTA was found to be in good agreement with our simulations; however, the existing beamline design could not provide a perfect match into the linac. The matching range of the IMS was insufficient to handle the somewhat low brightness of the present beam. A redesign was proposed in which the PMQ steerer magnets would be rebored to lower their gradients. The proposed design is capable of matching a much wider range of beams exiting the radio-frequency quadrupole (RFQ).

We created a specialized version of the ETRACEM code for the dual-axis radiographic hydrodynamic test (DARHT) project, adding features such as the ability to account for random errors in the magnets.

We designed a beam-redistribution system that produces uniform or hollow distributions at the target for the Energy Selective Neutron Irradiation Test (ESNIT) facility. We determined losses and effects of duodecapole components in the octupole magnets.

For the Accelerator Production of Tritium (APT) project, we designed a beam-redistribution system that produces a large uniform beam at the target and characterized the nominal beam-intensity distributions and their operational variabilities resulting from beam jitter, beam-energy shifts following rf-module failure, and beam-emittance shifts following accelerator-quadrupole failures. Because the specifications include multiple targets, the HEBT designs used rf deflectors.

For the Los Alamos Neutron Scattering Center II (LANSCE II) project, we identified and studied a candidate ring design and dimensioned its apertures to accept 1/3 of the beam required at 800 MeV and 5 MW. Additionally, we studied the ring design's injection chicane, bump-magnet scheme, and extraction section. We also identified a possible 2-GeV ring design.

In FY 1992 we designed optics and conducted studies for the Accelerator Transmutation of Waste, pion linac, International Fusion Materials Irradiation Facility, NPBSE, CEED, and the Luggage Detection System.

Beam Diagnostics Section

The AT-3 Beam Diagnostics Team was involved with several programs in FY 1992. The majority of our efforts were for the GTA program, but we also provided diagnostics support for the Advanced Free-Electron Laser (AFEL), Average Power Laser Experiment (APLE), APLE Prototype Experiment (APEX) Grumman Injector, and the Superconductor Super Collider programs.

The beam diagnostics team provided GTA with permanent and characterization beam diagnostics for several beam experiments, including tests for the IMS, which matches the beam from the RFQ to the input of the drift tube linac (DTL). The permanent beam diagnostics included within the IMS were three microstrip probes, a beam current monitor, and a video beam profile. A diagnostics platform or plate, for beam characterization has a transverse emittance measurement (typically described as a slit and collector emittance scanner), a beam current monitor, three more microstrip probes, a phase-spread measurement, and a longitudinal emittance measurement using a laser induced neutralization diagnostics approach (LINDA). Several papers have been written describing these various measurements and the data acquired from these systems and were published at the LINAC and PAC conferences this past year. Additionally, our team has written many AT-3 technical notes and several measurement operators manuals.

One beam diagnostics system completely designed, prototype, and beam tested in limited quantities was the beam-loss monitor system, which consists of an ion chamber and local preamplifier whose signal is cabled to

another processing electronics module. The complete beam-loss monitor system provides two functions for the GTA. The primary function is to provide a fast (< 10 ms) response signal if a catastrophic accident should occur in which the accelerator and beamline components are placed in peril because of direct beam impingement. For particle beam energies above 5 to 8 MeV, this interaction would produce lower energy gammas, which would be sensed by the system's ionization chamber. If the gamma dose rate is sufficiently high, a signal is sent to a fast protect system that, in turn, shuts down the beam source. The second function of the beam-loss monitor system is to provide smaller rates of beam loss, which in turn can give the GTA commissioners more information about the beamline and accelerator.

AT-3 also contributed to various electron beamlines attached to the free-electron laser (FEL). Both the AFEL and APEX facilities have received beam position measurement systems that use capacitive probes and processing electronics similar to those used for the GTA. Additionally, we began work on the APLE project, an electron linac/beamline for high-average power FELs at Boeing in Seattle, by performing beam tests on a flying-wire style of charged-beam profile measurements (FWBPM).

We modified the design of the prototype FWBPM system, originally developed for use on the GTA, to improve its performance and to adapt it to measure beam-profiles for the APLE/HPO high-current electron accelerator. The signal's amplitude, measured either directly off the wire, or indirectly from detectors located near the wire, is proportional to the beam that intercepts the wire. Hence measuring the signal as the wire moves through the beam will map out the beam profile along the axis perpendicular to the wire's motion. The APLE/HPO FWBPM system has a pair of 35-dia. micron carbon wires mounted at

right angles to one another on a 17-cm diameter wheel. The two orthogonal wires allow both the X and Y beam profiles to be measured in the same scan. A servo motor is used to accelerate the wheel from rest to its peak speed in less than half a revolution, at which point the two wires intercept the beam and the wheel is decelerated back to rest before completing one full revolution. The electron beam that intercepts the wire produces secondary electrons that are detected either by measuring the charge depletion current on the wires or by collecting the secondary electrons on a pair of positively biased collectors mounted up and down stream of the wires. The goal of this system is to measure the profile of a ~1 ms-long, ~1 mm-diameter high-current electron beam with a resolution of 100 μ m or better without over heating and breaking the fine carbon wire. For the wires to survive in the APLE/HPO beam, the wire must be capable of sweeping through the beam at a speed of 20 m/s or better. Achieving these speeds in just half a revolution does not leave enough time for the wheel velocity to stabilize before the wires sweep through the beam. To overcome this problem, the wheel velocity is recorded as the wires move through the beam, allowing the data to be corrected for any variations in velocity.

The APLE/HPO FWBPM system has been tested at the APEX electron accelerator using a high-intensity low-duty beam of ~40-MeV electrons. However the typical macropulse length of the APEX beam is too short (< 20 ms) for the moving wires to intercept. Instead the wires were moved slowly through the beam to map out a beam profile averaged over many macropulses. Preliminary results indicate that the signal strength measured from the wires and charge collectors agrees with the calculated signal strength; and a preliminary beam profile measurement also indicates that the profile measured with this system had roughly the same shape and width as the profile observed on a nearby

video screen. We will conduct future studies to refine this measurement, to determine the measurement resolution, and to determine which method of signal detection yields the best results. Preliminary results indicate that the signal-to-noise ratio is considerably better on the charge collection ring, which if accurate would greatly simplify the mechanism by eliminating the need to make electrical contact with the wires mounted on the rapidly moving wheel.

Finally, we delivered several toroids (beamline devices used to measure beam current) and a microstrip measurement system to GAC. We have extended this contract to include two more microstrip systems which will be used with a small test stand for experiments with injector automation experiments.

Magnet Section

Magnet Measurement

In July 1992, we completed our final cryo mapping of the permanent magnet DTL quads for the GTA. Over 200 cryo maps were taken to measure the gradient length (GL) product vs temperature (T) dependence of the 140 PMQs need for the DTL. This effort occurred over a year and a half as the magnets were received from the vendor. The cryo mapper specifically designed for this task worked remarkably well; once operational, it experienced very little down time. It measured the GL vs T of the cryo quads from room temperature to 20K and back to room temperature with an absolute uncertainty of $\pm 0.5\%$ in a cycle time of approximately 3 hours per magnet.

A Rotating Sample Magnetic Moment Mapper (RSM3) was built by the AT-3 magnet lab to measure the direction and magnitude of the magnetic moment of permanent magnet material samples. The design for the RSM3 is patterned after a similar device built by Lawrence Berkeley Laboratory.^{1,2} It consists of a pair of 45-cm diameter coils each

wound with 850 turns of #30 copper wire. The coils are placed in a Helmholtz configuration, and the sample to be measured is rotated at the center of the two coils by a small direct current (dc) motor. A 1000-pulse per revolution incremental encoder is connected to the dc motor, and the coils' voltage is integrated and read in every 20 encoder pulses by a Metrolab digital integrator. Data acquisition and control are through a GPIB interface to a Macintosh IIfx running Labview. Magnet segments are mounted in a cubical holder that orients the sample's x, y, or z axes parallel to the axis of rotation. The amplitude and phase of the signal, measured as the sample is rotated on its three axes, determines the magnetic moment in the plane perpendicular to the axis of rotation. These results can then be used to calculate the x, y, and z components of the magnetic moment, the overall magnitude (M), and angular deviation of M from the desired orientation (DQ). The uncertainty in the absolute measurement of M is estimated to be $\pm 1\%$, and the uncertainty of determining the absolute DQ is estimated to be $\pm 0.5^\circ$. The relative uncertainties of M and DQ are much better, $\pm 0.05\%$ and $\pm 0.25^\circ$, respectively.

Magnet Design and Fabrication

Four variable field permanent magnet quadrupole (VFPMQ) doublets and one singlet were designed and fabricated by AT-3 for use on the AFEL. The basic design of the AFEL VFPMQ is similar to the magnets built for the GTA IMS, which are patterned after the conceptual design proposed by K. Halbach.³ The magnetic design criteria for the magnets were a clear bore diameter of 26.2 mm, a quadrupole gradient that can be continuously varied from 0 to 60 T/m, minimal allowed harmonics, and 35-mm-long pole tips. Two key mechanical design features of these magnets were that the doublets were made by mounting two VFPMQs 1 cm apart in the same housing and that the polarity of each VFPMQ could be easily reversed without disassembling the unit. The mechanical design was

found to work well and the magnetic measurements were in excellent agreement with the calculated results. The magnets were installed on the AFEL and have been in continual use since June 1992.

Additional subroutines for three-dimensional modeling of large-bore optics elements were incorporated in MARYLIE and TLIE, the two high-order optics codes being developed in collaboration with the University of Maryland. These new subroutines allow us to compute error effects, including "hidden" multipoles in permanent magnet quadrupoles, i.e., field components arising from axial components of magnetization. These field components integrate to zero and are not seen in integral field measurements, but can affect higher-order optics.

A preliminary design for a prototype ferrite kicker magnet module for use in proton storage rings was completed in FY 1992. The design incorporates various features to minimize the rise time, including use of a parallel speedup capacitor and a series saturable inductor.

The cylindrical current-sheet magnet concept was extended to short iron-free quadrupoles. These magnets are designed to produce a magnetic field with nearly perfect $\sin 2\theta$ symmetry about the beam axis; the residual integral error multipoles due to finite-turn-number effects are zeroed out by small shifts in the conductor positions specified by a computer algorithm developed in 1992. Precise conductor placement is achieved by fixing the superconducting wires in grooves that are machined in a particular pattern in a cylindrical surface by a numerically controlled milling machine.

Mechanical Design, Fabrication, and Assembly Section

The mechanical design, fabrication and assembly section provides design, quality control of design packages,

liaison work, fabrication, assembly, installation, machining, welding, and vacuum leak certification. This service supports other sections within AT-3, AT Division, other accelerator laboratories, Grumman Aerospace Corporation, the U. S. Navy, Boeing Space and Science Division and the GTA program.

Some of the components that this section has provided are: beamline diagnostics, full sections of beamlines, experimental beamlines, beamline support structures, resistive dipole and quadrupole magnets, harps, vacuum boxes, steering magnets, Lambertson-type correction dipoles and quadrupole magnets, variable field permanent magnet quadrupoles, and variable field permanent magnet dipoles.

Future Plans

Our future plans are to complete the beam diagnostics for the GTA accelerator and begin the beam diagnostic work for the GTA bend and telescope. We will continue to build beam diagnostics for APLE, and increase our diagnostics support for SSC.

We will increase our magnet design, building, and mapping support for the SSC. We also anticipate building magnet mapping devices for the SSC.

The AT-3 optics section will support the bend and telescope design for GTA, support storage ring design for LANSCE II, and support the ABC projects with optics design for creating uniform beam illumination target design, and increase our support for the SSC.

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Introduction

AT-4 represents one of the strongest mechanical engineering organizations at the Los Alamos National Laboratory (LANL), combining the individual strengths found in other Laboratory mechanical engineering organizations and focusing them on the design of radio-frequency (rf) accelerators. The group is currently composed of five sections: analysis, mechanical engineering, mechanical drafting, test engineering, and drawing production and quality assurance (QA). The centralization of these sections has allowed us to build a stronger capability in AT Division.

The engineering analysis section has developed and supported a sophisticated analysis capability incorporating PATRAN/ABACUS software and Silicon Graphics engineering work stations. This system allows us to model both the structural as well as the thermal response of very complex geometries as well as the vibrational response of systems. The analysis section is also responsible for developing computer aided engineering (CAE) techniques for accelerator development. We are currently using these techniques to build cold models of complex rf structures using a stereo-lithography technique. The basic goal of the project is to build an actual cold model of the part in a few hours based on an electronic model of the part (computer aided design [CAD] solids representation) using a stereo-lithography technique combined with a copper deposition process. This electronic model would also be coupled with our thermal and structural analysis software to allow us to analyze the part from a common data base.

Our mechanical engineering section is responsible for the mechanical design of accelerator components, including engineering accelerator cavities, magnets, couplers, diagnostics and beam line components such as vacuum vessels, support structures, and cooling systems. This section is also respon-

sible for designing cryogenic accelerator components as well as for developing and implementing the engineering methodology necessary to the success of our projects. Methodology includes physics and engineering criteria definition documents, a design review process, value engineering, and training new engineers.

Our mechanical drafting section produces machine drawings that vary in scope from sketches to manufacturing drawings. Manufacturing drawings are produced using geometric tolerancing to ANSI Y14.5 standards and incorporate drawing system requirements based on DoD-D-1000 standards. The drafting section incorporates a formal drawing checking procedure as well as a formalized drawing change procedure. This section uses a CAD system with SiG stand-alone work stations, which operate in a secure environment, and ICEMDDN CAD software. In addition, the mechanical drafting section manages the electronic archival of drawings.

The test engineering section is responsible for assembling and testing hardware designed by the engineering and design sections; designing assembly and testing fixtures; and assembling complete accelerator cavities including tuners, magnets, positioning devices, rf couplers, diagnostics, and cooling manifolds. Typical testing involves pressure and flow testing of accelerator cavities, vacuum and cryogenic testing of components, load, positioning, and repeatability testing of magnet positioners, and testing of rf tuners. This section operates three cryogenic test facilities capable of operating at 20K with refrigeration capacities up to 750 W and operates a vacuum laboratory that incorporates ultra-high vacuum test apparatus.

Our drawing archival and QA section is responsible for drawing production, reproduction, hard copy archival, and QA functions in the group. This section also operates the drawing security vault and maintains the security re-

quirements for CAD systems as well as for drawings. Responsibilities also include meeting the Department of Energy (DOE) program requirement for three levels for drawing archival as well as for adhering to a drawing system. In addition, DOE programs are beginning to apply QA procedures to the design process by requiring design reviews, design notes, and specifications documentation. Consequently, this section is responsible for implementing these QA functions for the other sections in the group as required.

In FY 1992, we have witnessed several successes in project related activities within the group. The Ground Test Accelerator (GTA) has been commissioned up to and including the first drift tube linac (DTL) module. This accelerator, engineered and constructed by AT-4, has been immensely successful; both the RFQ and the DTL have operated flawlessly. The intertank matching section (IMS), which required the rf couplers be redesigned and the steering magnets be modified to account for a broader operating requirement, has also been a success, particularly because it is such a highly complex piece of hardware. AT-4 has also successfully progressed toward a preliminary design of the GTA optics system and is beginning the conceptual engineering design of an upgrade to the Proton Storage Ring facility, which could represent a major engineering project in the next few years. The group has continued to provide engineering support to other groups and divisions associated with accelerator work. We participated in the superconducting RFQ design, an accelerator for the Federal Aviation Administration for baggage inspections, and supported the beamline components design for the Clinton P. Anderson Meson Physics Facility (LAMPF) accelerator. We are a maturing organization who has developed the key elements to support a successful engineering organization.

Achievements

GTA

DTL Assembly and Testing

The drift tube linac (DTL) comprises the major portion of the 24-MeV GTA. It consists of 10, 1-meter long, 850 MHz cavities containing a total of 130 drift-tubes. It resides immediately downstream of the Intertank Matching Sections (IMS) on the GTA beamline.

Four DTL modules have been completed through high power rf acceptance testing at operating temperature (20K). One additional module is completely assembled and in the process of testing. The remaining five modules are in various stages of assembly.

All components are available except the remaining drift-tubes for modules #8-10, which are being completed at Westinghouse Hanford Company. During FY 1993, final assembly and testing of the remaining DTL modules is planned for eventual installation on the GTA beamline.

Acceptance testing of each module is an extensive set of tests consisting of (1) room temperature alignment of the drift-tubes, (2) room temperature resonant frequency tuning of the cavity, (3) flow orificing and pressure/leak testing, (4) low power cryogenic testing to evaluate changes in drift-tube alignment and resonant frequency from room temperature, and (5) high-power rf conditioning of the cavity prior to installation on the beamline. The DTL modules appear to

be operating as expected through the high-power conditioning phase.

Figure 4.1 shows module #1 completely assembled before installation into the DTL vacuum vessel for beam experiment 2A. Module #1 has been operational on the GTA beamline for beam characterization experiments since early September 1992. This module has been operating as expected with no apparent problems. Figure 4.2 shows 8 of the 10 DTL modules in various stages of assembly to indicate the complexity of the assembly process as each module is built up to be fully operational.

Waveguide Basement Floor Analysis and Installation

Upon completion of experiment 2A, we will move the GTA experiment from the tunnel's northeast corner to the south side of the tunnel and position it directly over the waveguide basement. Consequently, we significantly modified the existing tunnel floor dynamic-input spectrum. Because the accelerator will now be supported on a suspended strongback, we are confronted with additional design challenges. Initially, the DTL accelerator was designed for a dynamic-input spectrum in the previous, more benign, stable location. In its new location, it will be exposed to more background lateral vibration sources (e.g., pumps and compressors) than the original, conventional support structure was designed to accommodate. As a result, the floor was laterally isolated from the north wall, but still is able to support vertical loads.

Fig. 4.1. Fully assembled drift tube linac (DTL) module #1.

Fig. 4.2. Assembly stages of drift tube linac (DTL) modules (Juanita Romero, AT-4).

AT-4 and MEE-13 had initially developed a finite element model of the DTL assembly from the base of the module support pedestal to and including the drift tube mounted into the DTL module. Following vibrational analysis, we found this model's drift tube displacements were very small and could therefore be neglected. MEE-13 measured the dynamic response of the floor around the waveguide basement in 1992 and updated the dynamic model to include the new strongback. It was then found that the vibrations at the interface to the basement's north wall caused larger drift tube displacements than the previous model had indicated. Beam dynamic analyses showed that these drift tube displacements produced enough of a steering error to give an unacceptable apparent emittance

growth. These simulation efforts identified the level of vibration isolation required, such that the resultant inputs to the base of the support pedestal are at or below the original design environment. In addition, a modal survey was done using DTL module #4 to verify the finite element model results. These results indicated the strongback needed to redistribute loads while maintaining the required alignment during accelerator operation. The structure had to be stiff enough to preclude deflections during operation at high vacuum after alignment at atmospheric pressure. During high-vacuum operations, the 6000 lb vertical up load at each of the 10 DTL pedestals must be balanced by the 60,000 lb vertical load distributed over the vacuum vessel floor. A structural finite element model was devel-

oped to validate the resultant design. Figure 4.3 shows one of the three waveguide floor modules before installation into the GTA tunnel. The numerous cutouts shown provide access for rf waveguide and utility feedthroughs. The three floor sections were delivered in August and have been installed into the GTA tunnel. The numerous cutouts shown provide access for rf waveguide and utility feedthroughs. The three floor sections were delivered in August 1992 and have been installed in the GTA tunnel.

Fig. 4.3. Ground test accelerator (GTA) waveguide basement floor module.

Optics Design

The GTA optics design went through several changes again in FY 1992, including conceptual designing, costing, and scheduling. At the beginning of the fiscal year, efforts were directed toward designing and building a "space qualifiable" optics system, meaning the hardware would be designed for a space mission, but not tested. However, if funding were to become available, the system could be tested and flown. Consequently, we created a conceptual design of the system and built preliminary thermal, structural, and dynamic finite element models. The thermal model determines both spatial and time-varying temperature profiles of the space structures and their magnets, including the on-orbit environmental heat fluxes such as solar, albedo, and the earth's infrared. Dynamic and structural models were built using beam and shell elements, respectively, to interface with the existing Titan III model McDonnell Douglas established for the neutral particle beam space experiment (NPBSE) in 1991. These models enable parameters such as mounting schemes to be optimized for minimized weight. Much of the required interface data such as geometric relationships to other spacecraft hardware, internal heat sources and weights, and launch and space environment dynamic loads were developed from past reports (e.g., NPBSE, NPBIE).

During the fiscal year the design focus changed to match the actual program funding. The change eliminated the term "space qualifiable" from the hardware description and replaced it with "space cognizant," meaning the optics system would look as if it could go into space, but there would be no analysis to support the design. The high-energy beam transport (HEBT), eyepiece, and steerer would be designed as ground experimental hardware only and would not be required to be space compatible. The change eliminated the term "space cognizant" from describing the telescope. The bend, shown in Fig. 4.4, was still to remain as a space compat-

ible item and was designed as a pseudomonocoque or truss structure. This design addressed and met its goals: an efficient lightweight structure to carry flight and launch loads, maintain the precise magnet alignment requirements, maintain the particle beam axis in line with the structural axis to reduce high-interface stresses from eccentric load paths, provide maintenance and accessibility to the beam diagnostics and magnets, and have a reasonable assembly and commissioning plan.

The design change resulted in us splitting the optics program into two paths. The first direction was to design the 24-MeV ground telescope and eliminate the bend entirely, which would leave the GTA accelerator on the north side of the tunnel facing west. We completed a work breakdown schedule and cost estimate to determine if the hardware and labor savings would offset the utility and facility costs associated with leaving the experiment in its present location. The second direction was to go back to a space design to support the far-field optics experiment (FOX) headed by Grumman with team members from McDonnell Douglas and LANL. The FOX is a 5-MeV "straight shooter" with a single joint enabling the telescope to be folded for storing dur-

ing launch. Consequently, this effort involved making layouts and performing preliminary dynamic and thermal analyses.

After the cost estimates and tradeoff analysis were completed, we decided the GTA experiment would be moved to the south wall where it would face east. Four other optics systems were investigated to help reduce the overall cost and schedule. The first was an 8.5-MeV ground "straight shooter," which would follow after DTL module #5 was considered, eliminating the cost of installing the five remaining DTL modules and delaying the bend design and fabrication until a later date. The telescope would be designed so it could be upgraded to a 24-MeV configuration. The second optic system considered was to design both an 8.5-MeV bend and telescope and install them after DTL module #5, with both assemblies potentially upgradable to 24 MeV. The third design would be an 8.5-MeV space optics system, which would compete with FOX for funds set aside for a space experiment. The fourth system involved designing a 24-MeV ground system that would be installed after the initial DTL experiment when funds became available. After evaluating design configurations, cost estimates, future plans, and sched-

Fig. 4.4. Ground test accelerator (GTA) optics bend design.

ule impacts, the fourth choice was chosen as the program direction.

Once the program focused on the 24-MeV ground optics system, we completed a conceptual design of the bend. After reviewing the available tunnel layout, vibrationally unstable floors, and the logistics of multiple set-ups, an active alignment scheme using theodolites did not seem feasible. Therefore, the design presently evolving uses tight tolerances, a quadrupole assembly fixture with taut-wire alignment apparatus, and a coordinated assembly plan to ensure the bend magnets are properly aligned.

Design of the Accelerator for Production of Tritium (APT) and Transmutation of Waste (ATW)

Since the conception of LAMPF, the greatest challenge for the linac designer has been to engineer high-current, continuous-duty machines; several of our present studies involve such machines. During 1992, AT-4 led the engineering design, under a DOE study contract, for a 200-mA, 1000-MeV, cw, water-cooled machine called the Accelerator for Production of Tritium (APT). This work has required that we develop new cavity structures, and solve special cooling and maintenance problems, setting the stage for other machines of a similar nature.

A conceptual design for the APT accelerator has been in progress during FY 1992. This accelerator consists of a pair of 100-mA proton sources feeding two RFQ's that operate at a resonant frequency of 350 MHz raising the beam energy to 7 MeV. The beam is then delivered to DTLs designed for 350-MHz transmission, further raising the energy to 20 MeV before the two beams are funneled into a single 200-mA beam with a microstructure frequency of 700 MHz. At this point, a new accelerating structure is evoked, called a bridge coupled DTL (BCDTL), to carry the beam to 100 MeV. At 100 MeV the beam power is 20-MW cw and must be handled with extreme care.

The beam is injected into a side-coupled linac structure similar to LAMPF where the beam is accelerated to 1 GeV before it is directed to the tritium production targets.

While this study involves the concept of using a machine to produce tritium, with minor adjustments in output energy and current, the machine can be used to treat radioactive waste (i.e., Accelerator for Transmutation of Waste [ATW] or Accelerator Based Conversion [ABC]) or act as a neutron factory of unprecedented flux. It is, therefore, a design with wide ranging applications. The basic design, however, is water-cooled and conventional in nature as compared with more exotic superconducting approaches.

Mechanical Design

One of the key decisions we made early in this study was to use electromagnetic quadrupoles in the DTL to resist radiation effects. Even small losses in a 200-mA proton beam at

elevated energies will produce sufficient neutrons above a few MeV to significantly shorten the lives of rare earth cobalt-magnet materials. Using electromagnetic quadrupoles in the DTL, which dictate the minimum size for the DTL drift tubes, coupled with the need for continuous-duty rf sources, resulted in our choosing the 350 MHz for the front end of APT.

Following the funnel at 20 MeV, we identified a more difficult problem: the need for low-energy, large-bore, high-frequency (700-MHz) structure to accelerate the beam to its final energy. It was evident that a standard coupled cavity linac (CCL) would function well, but only at 80 or 100 MeV and above. To bridge the gap between 20 and 100 MeV, we needed an entirely new structure to avoid the structural, cooling, and operational problems of a very low-energy CCL. We developed the BCDTL for this purpose (Fig. 4.5). It consists of short accelerating modules, seven beta-lambda in length, which the

Fig. 4.5. BCDTL 700-MHz accelerating tank at 20 MeV.

beam dynamicists find give excellent beam transport results. We placed quadrupole doublet focusing magnets for strong focusing between modules at short intervals. Each of the BCDTL accelerator tanks holds six drift tubes, unique in that they do not carry quads. In addition, the drift tubes have extremely large bores considering the high frequency at which they must operate. Because there are no quads in the drift tubes, alignment tolerances can be more lenient (± 0.5 mm). Consequently, the drift tubes can be "hard socketed" for good rf seals, which are necessary for cw operation. The aperture ranges from 4 cm in diameter at 20 MeV to 5 cm at 100 MeV. It is desirable to achieve a high-aperture ratio of bore diameter to beam diameter to prevent beam losses and radioactivation by the beam. The BCDTL effectively overcomes the problems caused with an equivalent CCL at the same low energies by eliminating the close-spaced rf surfaces, multipactoring, and other operational difficulties. Also eliminated are cooling and fabricating problems, and inefficient rf operation result-

ing from the inherent low-shunt impedance of a CCL structure below 100 MeV. Figure 4.6 shows a four-tank assembly of a BCDTL module.

Once the beam energy has been raised to 100 MeV, a conventional pi-mode CCL is the best structure to use. The shunt impedance is now higher than a BCDTL and the fabrication and cooling problems are greatly diminished. A precedent also exists in LAMPF for CCL structures fabricated at this entry energy, although at 700 MHz, the APT cavities are 15% larger than LAMPF and marginally difficult to braze. This factor is another reason why the choice of 350 and 700 MHz was made for APT. Below 700 MHz, a CCL becomes difficult to build because of its increased size and bulk. The frequency choice that was selected is ideal from an engineering, cavity structures and fabrication standpoint.

The 100-MeV CCL module, shown in Fig. 4.7 represents over 300 such modules in the CCL, which compose 90% of the bulk and cost of the APT linac.

Fig. 4.6. Bridge coupled drift tube linac (BCDTL) module at 20 MeV.

Fig. 4.7. CCL Module at 100 MeV.

This structure is designed around a single half-cell concept in which half the coupling cell and half the accelerating cell are machined into the same forging. This is a departure from the technique used at LAMPF in which the coupling cells were brazed as separate assemblies. However, by splitting the accelerating cells along the septum midplane, it is now possible to machine adequate cooling channels to accommodate cw operation of the structure because septum rf heating is of primary concern in a cw CCL. Along with the septum cooling channels, an internal channel is also machined around the coupling cell periphery. A cross section of the resulting septum cooling channels is shown in Fig. 4.8. The entire cooling system for a seven beta-lambda long structure consists of longitudinal gun-bored cooling channels around the periphery of the tank assembly distributed in pairs, with each pair feeding a single septum and coupling cell. The flow is mass balanced and confined to counterflow, which results in a uniform temperature distribution along the length of the tank. Development of this cooling scheme along with the BCDTL constitute two of the major engineering breakthroughs in the APT linac design.

A third significant design development is based on the potential need to perform maintenance on beamline components under radioactive conditions, which demands quick or even remote servicing. We found the principal components subject to failure are the vacuum pumps, the rf windows, and the intertank beamline components, which include the doublets, diagnostics, steering dipoles, bellows, and a rad-hard vacuum valve. All the intertank hardware is mounted on a pair of rails for quick removal and ease of alignment as shown in Fig. 4.9. The hardware is constrained to fit into a longitudinal space of 3.5 to 5 beta-lambda depending on the energy point being considered. The unit can either be fully disassembled on line, if conditions permit, to replace field coils, or it can be partially disassembled to changeout valves or bellows. It can also be removed en-

tirely and taken to the lab for total overhaul, perhaps in a hot cell. A replacement unit, prealigned in the lab and completely checked out, could then be slid onto the rails providing predetermined alignment with the as-installed hardware.

The entire APT is designed to be modular in that each klystron amplifier drives a segment of the accelerator using from 600 kW to 1.25 MW of total power. Each accelerator module is mounted onto a rail system complete with a self-contained vacuum system, water-cooling manifold, focusing system, diagnostics and essential instrumentation. It is prechecked, aligned, and rf conditioned offline and then transported to the machine tunnel where it is installed on prealigned kinematic mounts. This modular approach allows the machine to be maintained either in sections, off line, or removed

as a complete unit for major repairs.

The general APT design described above is applicable to any proposal for a water-cooled, funneled machine in the 300- to 900-MHz range that accelerates protons to energies of 1 to 2 GeV, operates at beam currents up to 350 mA, and functions in a cw mode. This APT study has been a great engineering challenge, has placed us in a position to deal with similar machines for radioactive waste disposal, and has shown potential for future applications.

Seven-Cell Superconducting Cavity and Superconducting Cavity Chains

One of the most advanced superconducting cavity prototypes was designed and released for fabrication during FY 1992 after a collaborative effort between AT-4 and AT-1. The prototype consists of seven cells of high-

Fig. 4.8. Coupled cavity linac (CCL) septum cooling channels for high-duty factor operation.

Fig. 4.9. Quadrupole doublet alignment and quick maintenance hardware for radioactive applications.

purity niobium welded together into a 805-MHz cavity chain. Unique features of this cavity include its extremely high unloaded Q (5×10^9) when operated at superfluid helium temperatures (2K) and the high fields expected in the structure (12.5 to 15 MV/m) at this relatively low frequency. The 805-MHz resonant frequency implies that a large surface area will be exposed to high field levels. The successful test of this prototype would be a benchmark in coupled cavity superconducting technology.

A representation of the seven-cell assembly is shown in Fig. 4.10. Individual cells are electron-beam welded at the equators and iris. The cavity subassemblies are then acid etched, tuned, and annealed at high temperature using titanium gettering to remove surface impurities. Cavity assembly inside the stiffening cage of six titanium tubes ensures that microphonic resonances exceed 240 Hz in the lowest transverse mode for adequate rf stability.

Also shown in Fig. 4.10 is a four-bar flex linkage for fine tuning. This linkage is expanded in Fig. 4.11. Fine tuning is accomplished by deforming the end half-cells of the cavity chain.

Fig. 4.10. Seven-cell high-gradient superconducting cavity showing areas of advanced technology.

Fig. 4.11. Four-bar linkage used to achieve microtuning of the end half-cells of the seven-cell cavity.

One must be careful to work within the elastic limit of niobium at superfluid temperatures; however, the tuning sensitivity of the system is almost 320 KHz/mm and the elastic tuning range is ± 41 KHz. To achieve this tuning range, the adjuster compresses or expands the end cells by only ± 0.13 mm. Because of the extremely high Q of this cavity chain, the linear yoke motion of the actuator necessary to achieve a 1-Hz step in cavity frequency is only 250 Å (2.5 mm).

The seven-cell design departs from conventional engineering methods in several other ways, including the use of commercial metallic seals rather than indium. Indium is a good sealing material at superfluid temperatures, but tends to flake. Even the smallest particle falling into the cavity will destroy its high-field capability. To use the commercial Helico-flex Delta-Seal requires that niobium alloy flange material be selected with a Vickers hardness greater than 100. We selected an

alloy consisting of 10% hafnium and 1% titanium in niobium and tested it for weldability to pure niobium and resistance to superfluid helium leaks.

The seven-cell design described above is a research cavity with various uses, including pion or proton acceleration at medium energies. It is scheduled to undergo rf testing at full power in FY 1993.

Vibration Analyses

Because of an inherent sensitivity to microphonics, superconducting cavities must be designed to resonate at relatively high frequencies, despite the low stiffness of the basic thin-walled niobium structure. To raise the fundamental frequencies of this type of cavity, proposed stiffening schemes must be analyzed to determine if the required fundamental frequency levels are achieved. Finite element models of several superconducting cavity structures have been built to determine their fundamental resonant vibration modes.

Based on a highly favorable comparison between the finite element model of a CERN/DESY four-cell cavity and actual vibration test data of that cavity, we analyzed the LANL seven-cell cavity. Various stiffening schemes were proposed and analysis was done to arrive at an optimum stiffened configuration. The resultant method for stiffening the rf cavity consists of a structure with six titanium tubes connected at either end with a bulkhead, to which each cavity cell equator is rigidly attached. This simple structure raised the first (lowest) transverse bending mode from 37 Hz to more than 240 Hz. Based on this success, we constructed a similar analytical model to represent a nine-cell cavity currently being developed at the Continuous Electron Beam Accelerator Facility, where a novel stiffening concept is being considered that encases the entire cavity within a thin-walled cylinder.

Fine Frequency Adjuster Mechanism

The seven-cell cavity 'fine' tuning procedure involves elastic deformation of the cavity's end half-cells. We have designed an adjuster mechanism to effect this end-cell deformation via longitudinal translation of the cavity end flanges. It is mounted between the stiffening rod bulkhead and the cavity end flange (Fig. 4.11) and is similar to a four-bar linkage, but relies on flexures to eliminate the possibility of backlash and hysteresis. The adjuster is actuated through a yoke attached between two adjusters on either side of the cavity. Translation of the yoke rotates the center flexure, which in turn causes longitudinal expansion or contraction of the adjuster via a four-bar linkage motion of the outer flexures. A detailed three-dimensional, finite element model of the adjuster mechanism was created (Fig. 4.12), representing half of one adjuster. Although the niobium cavity is not directly included in the model, spring elements are used to represent its stiffness. We analyzed several different loading conditions to explore the various operating environments.

Fig. 4.12. Finite element model of adjuster mechanism.

Recently, a modified version of the seven-cell fine-frequency adjuster mechanism has been adopted by Cornell's Newman Laboratory of Nuclear Studies for use on a single-cell superconducting cavity.

Support of Others

Group N-2 FAA Moderate Energy Beam Transport (MEBT) System

Los Alamos National Laboratory's Group N-2 has purchased a 2.75-MeV RFQ from AccSys Technology Inc., which will be used in experiments to determine the feasibility of using a resonance absorption technique to detect nitrogen bearing plastic explosives. AT-4 was asked to design and fabricate a moderate energy beam transport (MEBT) system for use on the exit of the RFQ. The MEBT contained four electromagnet quadrupoles (EMQ)

obtained from the Accelerator Test Stand project in AT Division. The EMQs were retrofitted with new mounting devices, which provided four degree-of-freedom precision adjustments. The mounting devices also incorporated kinematic mounts, which allowed for removal and repeatable replacement of the 100 lb. EMQs. A small 1-cm-bore permanent magnet quadrupole (PMQ) was mounted on the exit of the RFQ in a vacuum tight holder. Provisions were made to monitor beam current along the beam line using two Model 150 Pearson coils. The entire MEBT assembly was mounted on a support stand, which provided adjustment in the x, y, and z axes. In July 1992, the MEBT was assembled and aligned at AccSys Technology. Acceptance testing and operational experiments are currently being

conducted by N-2 personnel. Figure 4.13 shows the MEBT assembly currently being used by N-2.

We are currently designing a new MEBT for the next phase of this program. It will include a 90° bend in the -Y direction, eliminate two of the EMQs, incorporate a new support stand, and add diagnostics in the vertical leg. The new accelerator and MEBT will be installed in the UHTREX facility at LANL's TA-52.

Group N-2 Nondestructive Assay Barrel Scanner

AT-4 personnel assisted Group N-2 in the design of a combined thermal/epithermal neutron (CTEN) nondestructive assay diagnostic. This instrument will be used to interrogate TRU waste and provide the required

Fig. 4.13. Moderate energy beam transport (MEBT) system assembly.

characterization for proper disposal. The device will be fabricated and commissioned at N-2 before shipment to the Idaho National Engineering Laboratory for final installation.

The CTEN diagnostic is the latest version of a long line of neutron counting devices, and the design is very similar to earlier versions. Design changes have been limited to the addition of extra shielding and to upgrading the instruments and mechanical drive trains. The most significant design change has been to replace the drive trains used to manipulate the target and shielding door from chain and right angle gear drives to modular rodless cylinder units with servo motor controls. The replacement of hand assembled drives with modular units allows for significant savings in the amount of design detail required and in the assembly and adjustment phases.

We have completed the design of the top assemblies and work is progressing on the details of the shielding door and target positioning assemblies. These design modifications are intended to minimize the amount of time required for redesign and use the skilled fabrication craftsmen available at N-2.

Group MP-7 LAMPF Support Helium-jet Experiment

AT-4 is assisting MP-7 in an engineering and design effort in support of a LAMPF helium-jet experiment. This experiment requires a coaxial cylinder arrangement, which is shown in Fig. 4.14. A maximum of 10 atm of helium gas is introduced at the center of the left end of the coaxial assembly of concentric cylinders, expanding through the cone to an 8-inch-long chamber fitted with vertically mounted test foils. The helium is expected to flow parallel to the test foils in a laminar condition. At the right end of the 8-inch flow chamber is an array of capillary tubes that will extract the helium isotopes produced when the assembly is introduced into the LAMPF beamline at the A-6 target area. The annulus between the coaxial cylinders contains cooling water.

This assembly has the capability

of moving ± 2 inches about the center of the 8-inch test chamber in the x-y direction and normal to the beam.

Currently the design is completed with 50% of the hardware in procurement. A mock-up of this experiment is scheduled to start in early 1993 in the LAMPF hot-cell area. After completion of the mock-up and off-beam testing the assembly will be installed in the A-6 target area. Subsequent to the first experiment, we plan to design test chambers that can be quickly removed and reinstalled with new foils.

A-2 Target Area Upgrade

Personnel in AT-4 are also assisting in the upgrade to the A-2 target area at LAMPF. Redesign work is in progress to replace some existing hardware in the target area, including vacuum tubes, collimators, and coolant lines. In the process of replacing this hardware, we are improving the current method of extracting heat from the target area. To support this redesign effort, we are developing several finite element analysis models to analyze the target area's heat transfer characteristics based on the beam's power deposition on the target. Recommendations can then be made on the size and quantity of coolant channels necessary to cool the collimators and vacuum tubes.

Fig. 4.14. Helium-jet experiment coaxial cylinder.

Environment, Safety, and Health (ES&H)

In the interest of improving the group's formality of operations, AT-4 has adopted a graded approach with an incremental implementation plan to accomplish desired changes. The AT-4 environmental, safety, and health (ES&H) self-assessment plan has been completed, approved and implemented. Work is continuing toward accomplishing the goals outlined in the plan. Individual training plans for employees have been completed, and formal ES&H training for all AT-4 personnel is in progress. A tracking and filing system is in place that includes employee job specific technical training as well as ES&H training. We have continued to generate and resolve ES&H Action Sheets throughout FY 1992. AT-4 has taken an active part in self-inspections as well as division inspections. During the Tiger Team inspection in August 1991, 225 ES&H Action Sheets were generated. All but 20 have been resolved, and we are in the process of addressing these. Material Safety Data Sheet (MSDS) libraries have been established on the third floor of Building 365, in the group office, and in the drawing vault. In addition, a liquid chemical and chemically contaminated solid waste storage area has been established in Building 365.

AT-4 has completed the standard operating procedures (SOP) and normal operating procedures (NOP) documentation for all testing operations within the group. Detailed SOPs and NOPs for the high-power cryo test bed, the low-power cryo test bed, the pressure and mass flow test stand, operation of the drawing print machines and plotters, and use and change out of anhydrous ammonia tanks were written and placed under quality assurance document control. Other documents included the test supervisors manual for rf power conditioning and testing of DTL modules in the high-power cryo test bed.

AT-4 also introduced a QA controlled document system that includes a formal cover sheet, distribution control, and document change notice (DCN) control of all revisions to the document. We have used this control to formalize the issuance and revision of manuals and procedures that have been designated as needing better accountability.

The present AT-4 drawing vault is an advanced system with a print machine, CAD plotters, and computer links combined with microfilm, disk and hard copy archives as well as DCN records, computerized drawing lists, and classified document records. The drawing vault serves AT-3, AT-4, AT-5, and AT-10. By combining and making efficient use of this resource, these groups have realized a significant cost savings, improved quality, and better QA document accountability. The vault is an approved repository for classified drawings, documents, and CAD disks with a classification of Secret NSI or less. Proper marking, identification, and accountability of all drawing hard copies, document files, and disks is maintained. Issuing and tracking drawing numbers and DCN forms are required as well as maintaining uniform procedures, listings, and accounting records to prevent duplicates, lost originals, or damage to drawings, documents, or disks.

AT-4 has dramatically changed in the formality and awareness in which it handles ES&H issues.

References

1. S. J. Black and G. Spalek, "Calculation of Mechanical Vibration Frequencies of Stiffened Superconducting Cavities," 16th International Linear Accelerator Conference, Ottawa, Ontario, Canada, August 23-28, 1992, Los Alamos National Laboratory document LA-UR-92-2735.

Technical Memoranda

The following AT-4 Technical Memos were written during the report period.

1. D. Liska, "Vacuum Analysis of the 20-100 MeV BCDTL," AT-4:92-02, April 1992.
2. D. Liska, "Generalized Design Formulas for Low Energy Electromagnetic Quads," AT-4:92-03, April 1992.
3. D. Liska, "Vacuum System Design Cookbook," AT-4:92-04, April 1992.
4. D. Liska, "Extreme Limits of Operation for Compact Electromagnetic Quadrupole Field Coils, Including Poletip Performance and Maximum Focusing Impulse (<GL>) Generated," AT-4:92-05, October 1992.

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Introduction

AT-5 has a primary mission to develop high-power radio-frequency (rf) systems for particle accelerators. The key elements which make up the high-power rf systems are the high-power generators with their associated support equipment and the rf feedback controls.

The same expertise used to provide the high-power rf systems for accelerators is applicable to other areas. This provides AT-5 with other opportunities to develop technology and applications in radar systems, waste processing, and materials processing.

The following describes the programs and activities of AT-5 during FY 1992.

GTA

Overview

In FY1992, AT-5 integrated the 425-MHz rf equipment with the first of the 850-MHz hardware. This was AT-5's first opportunity to demonstrate the rf system as it was designed and built and as it applied to an accelerator.

AT-5 was responsible for significant input toward developing the controls and computer interfaces as well as the four main components of the rf system for the ground test accelerator (GTA). The four main areas we were responsible for were the 425-MHz tetrode amplifiers, the low-level rf (LLRF) controls, the 850-MHz cavity conditioning stand, and the 850-MHz amplifiers for the beam line.

The 425-MHz tetrodes are 300-kW devices that supply power to the radio-frequency quadrupole (RFQ) and to the two intermediate matching sections (IMS). AT-5 designed and built four systems with one as a spare. Even though the IMS requires only 50 kW for each cavity, all the tetrode designs were the same allowing for ease in manufacturing. The tetrodes have worked very well since their installation and have been improved since their

conception by adding new Allen-Bradley control systems. This has made interfacing to the overall GTA control system easier.

The 850-MHz conditioning stand is a stand-alone unit with its own power supply and capacitor bank. This system was the original prototype for the 850-MHz amplifiers that will be used on the drift tube linac (DTL) sections of the accelerator. The system is used continuously while we are building the DTL portion of the rf system. Because we have a dual-klystron modulator, we are able to condition cavities in the conditioning vessel while using the other klystron to drive the first DTL tank for experiment 2A.

The low-level rf design supports both field control and resonance control of the cavities. It also supports many pick-up loops enabling the accelerator physicists to monitor accelerator performance. Additionally, we provided the rf reference rack that distributes the 425-MHz and 850-MHz reference signal to the various rf and diagnostic components.

The high-power rf system for the 10 DTL tanks for experiment 2D is under construction. This system uses a 5-A high-voltage power supply and a single large capacitor bank that provides power to all 10 klystrons. The integration of the system will be performed in FY 1993. After this system is complete, we will retrofit the conditioning stand to upgrade it to the production design of the DTL systems.

GTA has been a showcase for AT-5 and has allowed us to demonstrate a wide variety of expertise in accelerator rf power.

High-Power rf System Development and Production

The GTA 850-MHz klystron amplifier system has many unique design features. By combining two klystron amplifiers in the same oil tank with a common high-voltage controller, we realize significant economy of hardware and system volume (Fig. 5.1). By using modern high-voltage modulator design techniques, we realize fiber optic control. Additionally a feedback circuit topology minimizes output amplitude droop from the klystron. An advantage of the mechanical layout is that almost all electronic components are located on a removable lid, easing maintenance and ensuring a minimal down time. In the unlikely event that a modulator unit fails, it can be quickly swapped out and repaired off-site.

Fig. 5.1. Two-klystron modulator.

A view of the first GTA production modulator being installed is shown in Fig. 5.2. When completed, the rf stations will be capable of producing over 12 Mw of rf power with a 2-ms pulse width and a 10-Hz repetition rate.

The control hardware and software for the GTA klystron systems have been optimized from the engineering prototype to provide more effective system interface and control. Each klystron stand has its own supervisory controller for equipment monitoring and sequencing. Unlike the previous stand-alone rf stations, equipment parameters and status must be transmitted to the GTA master control room. Each station must be ready before the accelerator can operate. An example of an improved local control screen is shown in Fig. 5.3.

We designed the klystron capacitor bank's energy-storage system with personnel safety as the utmost concern. Consequently, redundant discharge paths and charge-state monitors are included. To increase personnel safety, the GTA energy storage system includes ergonomic considerations and advanced protection electronics. The capacitor bank uses interlocked and hanging ground hooks in the capacitor vault entry doorway requiring the operator to physically remove the safety hooks before entry into the vault is possible. An electronic ground fault interrupter (GFI), a new implementation for this type of hardware, effectively protects personnel and equipment from lethal shocks. The system is interlocked such that if the GFI malfunctions or is nonoperational, the power system will shut down safely and inhibit further operation. Attentive engineering has also yielded a clean, corona-free system design.

A view of the 500-kJ capacitor bank system is shown in Fig. 5.4.

Fig. 5.2. Installation of first production modulator (left to right: Bill Reass, Bill North, John Bancroft, Phil Critelli).

Fig. 5.3. Local control screen for modulator.

Fig. 5.4. Capacitor bank (500 kJ) for GTA (front to back: Bill Reass, Bill North, John Bancroft).

RF System Integration with GTA

In FY 1992, substantial progress was made in integrating the GTA rf system. In April 1992, the rf systems team was formed to improve the reliability, availability, and operability of existing equipment for experiment 2A; to prepare for expansion to support experiment 2D; and to bring new rf components on line. The final fabrication stages of the rf klystron stations for the DTL are shown in Fig. 5.5.

Standard system engineering techniques were applied, albeit informally, to integrate the GTA rf system. Major hardware components were taken off line and run through an intermediate hardware and software integration and verification process. Several nagging reliability problems were attended to. Operator interface screens used for controls gain scheduling were rede-

Fig. 5.5. Drift tube linac (DTL) klystron station locations.

signed for easier use and increased fault tolerance. All system components were then reintegrated, along with their respective software, and the entire rf system was put through a verification procedure. As a result, the typical rf turn-on time for operations was reduced from 4 hours to under 1/2 hour. Also, rf operations have been essentially uninterrupted during beam experiments, with minimal operator interaction. The acquisition rate of quality experimental data during experiments is at an unprecedented high level due, in part, to these improvements in availability, reliability, and operability of the rf system.

Several activities are under way to ensure continued success in the GTA rf sector. We are developing a formal product-oriented work breakdown

structure and will negotiate an integrated requirements document and all required interface control documents based on this work breakdown structure. Formal verification processes will be instituted to track compliance to requirements. These efforts will further improve the design quality and implementation processes.

Automated Klystron Test Stand

The automated klystron test stand was designed and fabricated in FY 1992 to verify the manufacturer's performance data before the amplifiers are commissioned in the GTA. To monitor and record the status of a klystron, this test stand uses a LABVIEW-based data acquisition and control program (Fig. 5.6). The LABVIEW system interfaces with the Allen-Bradley PLC5/15 con-

troller that monitors and records the status of the power supply, transmitter, and other safety interlocks. Thus, LABVIEW automatically records the operating voltages and currents of each klystron as the tube is being tested. Three automated tests are performed to characterize the tube performance: swept frequency, power transfer, and a Rieke diagram. An example of swept frequency results is shown in Fig. 5.7. Ten out of the twelve Thomson klystrons were tested this year; test results are compiled in AT-5 memoranda.

RF Controls

In FY 1992, improvements in the Downconverter (DCM), Vector Detector (VDM), and Upconverter (UPM) modules allowed the design of the core LLRF system to be frozen. In Febru-

Fig. 5.6. Automated klystron test hardware.

ary, the three 425-MHz LLRF systems and the first 850-MHz system were integrated into the GTA. The LLRF system for the RFQ was upgraded to include module improvements to allow for a reduction in size. As a result, operational problems in the original configuration were corrected, and the LLRF system for the RFQ was reduced from three to two chassis. The two new LLRF systems for the IMS cavities were also integrated as two-chassis systems. We successfully integrated the new 850-MHz system for the DTL #1 cavity and demonstrated its proper operation. To support the 850-MHz system, we upgraded the rf reference rack to include 850-MHz as well as 425-MHz outputs.

To deliver this hardware as tested and operational, certain process advances were made. The Automated Test Lab was developed and constructed during 1992. The test lab includes the test console, test data storage, tested components, and instrument manuals as well as work space for component troubleshooting. The test console, shown in Fig. 5.8, contains a UNIX-based workstation capable of remotely controlling all the rack-mounted instruments and switching modules. All test software is written in Hewlett Packard's graphical programming language called VEE. We first demonstrated the facility in late 1992. A GTA UPM was completely tested with the facility. The console, testing software, testing fixtures, and cabling harnesses all had to be completed. During the testing, we reconfigured instruments, actuated switches, and recorded measurements in a totally automated manner for the complete module test.

We performed system testing on all five of the systems to verify the LLRF subsystem integration process before delivery to the GTA. In addition, we created a definite customer and acceptance test to enable system verification upon delivery to the GTA rf team. Lastly, operator manuals for all the modules were completed to facilitate understanding and troubleshooting.

Fig. 5.7. Sample of automated klystron test results.

Fig. 5.8. Radio-frequency (rf) control module test lab.

Feedforward Module

The Adaptive Feedforward Module, which was developed for the University of Twente, was tested in an experiment on the GTA. The feedforward topology is shown in Fig. 5.9. This feedforward module demonstrated the use of adaptive feedforward technology and provided a real method to extend the system bandwidth beyond the closed-loop control limit. Beam transient disturbances were nearly eliminated, an impossibility with the existing system. Figure 5.10 shows one of the error signals before and after feedforward is applied. The beam turn-on transient was almost completely eliminated with the feedforward. Additional implementation of the feedforward device on the GTA showed it to be a useful replacement for the current system. The theory may be used in the next generation of rf control equipment.

University of Twente

Los Alamos National Laboratory (LANL) entered into a collaboration with the University of Twente in the Netherlands to build a free-electron laser (FEL) for research applications. AT-5 was tasked by the University of Twente to build the rf controls, the rf driver, and the system interlock controls. AT-1 and AT-7 were tasked to provide other elements of the accelerator. (Figure 5.11 shows hardware installed in the University of Twente accelerator vault.) Based on previous hardware developed for the GTA, AT-5 developed new designs for the control software (based on LABVIEW commercial software) and for the klystron driver because of the specific frequency (1300 MHz) and power requirements (approximately 1 kW).

The high-power radio-frequency system for the University of Twente provided by AT-5 consists of a 1300-MHz preamplifier providing in excess of 1000 W of drive power (0.02% duty factor, 20- μ s pulse width) to the klystron; a waveguide run between the klystron and the accelerating structure; and a control terminal to monitor and control the high-voltage system. The klystron driver is a four-stage amplifier with three solid-state stages and one planar-triode cavity-amplifier stage. The monitoring and control system consists of an Allen-Bradley Industrial Controller and a T30 terminal, which provides the user interface. In May 1992, AT-5 delivered and installed this equipment and it is operating without problems. This hardware is shown in the left rack in Fig. 5.11.

The LLRF system developed for the University of Twente provides field control, resonance detection, accelerator timing, diagnostic monitoring, and alarm and limit monitoring for their FEL accelerator. This LLRF system was built into a single rack and included all LLRF equipment, an embedded Macintosh computer, a keyboard, a monitor screen, and all the necessary power conditioning. We also developed a LABVIEW software system for this system that runs on the embedded Macintosh computer and is stored on the computer's hard disk. Consequently, the university was provided with a complete, stand-alone LLRF control system. This hardware is shown in the middle rack in Fig. 5.11.

The LLRF system was completely tested and integrated at LANL to verify its operation before shipment. In addition, this system was used on the 1300-MHz AFEL system at LANL and performed successfully. The system was shipped to the Netherlands in August 1992. The university was provided with a complete set of documentation, including a system definition and user's manuals for all devices in the system. The university personnel used these documents, along with our assistance

Fig. 5.9. Feedforward system topology.

Fig. 5.10. Feedforward system test results on GTA.

via electronic mail, to perform much of the integration of the LLRF system with their accelerator. As a final training step, an AT-5 engineer traveled to the University of Twente to help with the final integration and to train personnel to operate the LLRF system. Currently, the initial results are favorable, although full system operation will be performed in FY 1993.

Boeing APLE

In 1992, we delivered a VXIbus-based LLRF system to provide rf field control, resonance control, timing, and diagnostic monitoring for the first four 433.33-MHz cavities of the Boeing Average Power Laser Experiment (APLE). We installed this system at Boeing in February 1992, and it was used successfully as part of their high-duty experiments that summer. Furthermore, we provided on-site training at Boeing to enable their personnel to understand, calibrate, and operate the LLRF system.

In addition to the delivered system, we negotiated a contract to deliver Boeing another LLRF system to accommodate the remainder of the FEL project. The new system will include another 433.33-MHz control system similar to the existing one, a new rf reference system, and a phase-stabilized transport system.

Argonne Advanced Photon Source (APS)

Argonne is building a new facility called the Advanced Photon Source (APS). AT-5 negotiated a design contract with Argonne to modify some of our existing rf control equipment to operate at 2856 MHz with a higher measurement bandwidth. This included design modifications for the Downconverter, Envelope Detector, and Vector Detector modules. The design work has proceeded well, with Argonne receiving and testing the engineering prototypes. Presently, the final designs are 50% complete and should be finished early in 1993. Argonne

requires many (40-80) of these modules for the APS project in 1993; therefore, LANL will be heavily involved in providing Argonne with these modules.

Superconducting Super Collider (SSC) Laboratory Linac

AT-5 has been working with the Superconducting Super Collider (SSC) Labo-

ratory on components for the linac for several years. The primary tasks have been to develop and fabricate a 427-MHz tetrode-based amplifier for test stand operation at the SSC and to develop and fabricate low-level rf controls. In addition to providing hardware, AT-5 has collaborated with engineers at the SSC on their system design, particularly the design of the feedback control system.

Fig. 5.11. University of Twente hardware installed in accelerator area.

The first control system was delivered to the SSC in early FY 1992. In addition, we loaned the SSC a cavity/amplifier simulator that allowed them to use the controls, apply disturbances, and measure responses. The simulator results were used by the controls personnel at the SSC to justify further development and fabrication effort. In the last half of FY 1992, almost all modules needed for two more complete

control systems were provided to the SSC; in addition, the SSC returned the cavity/amplifier simulator (after building a simulator of their own).

SSC and LANL collaborated to modify the design of the 425-MHz tetrode amplifier developed for the GTA to meet a 427-MHz requirement for the SSC. The GTA amplifier is a 300-kW pulsed amplifier with a maximum pulse

width of 2 ms and a pulse repetition frequency of 10 Hz. This design was modified to meet a 600-kW pulsed requirement for the SSC with a pulse width of 100 μ s and a pulse repetition frequency of 10 Hz. Fabrication was completed at LANL, and the amplifier was delivered to SSC and tested in May 1992. The amplifier design included a new lower-loss input cavity for the final amplifier and an upgrade in the

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Fig. 5.12. Tetrode amplifier (600 kW, 427 MHz) provided to Superconducting Super Collider (SSC) Laboratory.

Fig. 5.13. Power transfer curve for SSC Laboratory tetrode amplifier.

amplifier computer controls from the Pushbutton sheet-metal panel to a programmable terminal. In addition, the high-voltage power supply design for the final amplifier was drastically improved over the GTA design and has become our current baseline for this class of amplifier. The completed SSC amplifier is shown in Fig. 5.12 and a sample of the test results is shown in Fig. 5.13.

AT-5 has been involved with the SSC in designing and developing the low-energy booster (LEB) cavity since the beginning of the program at SSC. The AT-5 participation resulted from our experience with perpendicularly biased, ferrite-tuned cavities. This experience was gained during the Advanced Hadron Facility study at LANL.

The basic configuration for the SSC LEB cavity remains as originally proposed by AT-5. This configuration is shown in Fig. 5.14. The cavity is a quarter-wave resonant structure, with the accelerating gap at the high-voltage end and the ferrite torroids at the high-current end. Wave propagation is in the coaxial mode throughout most of the structure up to the ferrite region, where the propagation is in the radial direction. The control bias H field direction is across

the torroids in the longitudinal direction. The circuit's high-power excitation is provided by a 4 cw 150,000 E tetrode tightly coupled to the cavity through a coupling capacitor located between the accelerating gap and the ferrite tuner.

Fig. 5.14. Low-energy booster (LEB) cavity configuration for SSC.

Two different ferrite cooling techniques are being pursued by the SSC. The liquid cooling technique proposed by AT-5 is being developed at the SSC, while an alternate technique, using beryllium oxide disks glued to the ferrites, is being developed in Siberia by the Institute for Nuclear Physics Laboratory for the SSC. Tests at the SSC during the past year have validated water as a suitable ferrite cooling fluid within the rf structure.

In collaboration with the SSC power supply group, AT-5 modeled the magnet string in the LEB to characterize the magnet system's electrical design for the LEB, the first of five rings that make up the SSC. The LEB, which consists of 12 nearly equivalent magnet cells arranged in a 570-m ring, is designed to accelerate protons from 600 MeV to 12 GeV, and it can function in one of two modes (Fig. 5.15).

Fig. 5.15. Model of SSC magnet string for the LEB.

The primary operating mode is as a 10-Hz rapid-cycling proton synchrotron. In this mode, capacitor banks are used to make the entire magnet circuit resonant at 10 Hz (Fig. 5.16). However, because capacitor performance is affected by temperature change and the enclosure in which the capacitors are to be installed is unheated, total capacitance in the system is expected to vary as the daily ambient temperature varies. Therefore, to maintain resonance at 10 Hz, each capacitor bank includes additional trimming capacitors that may be remotely switched in and out of the circuit. This resonant system eliminates the requirement of otherwise having to provide (and recover) a large amount of reactive power.

Because the acceleration cycle is from 600 MeV to 12 GeV, the magnet current must swing a factor of 10, from 400 A to 4000 A. Because capacitors cannot conduct direct current (dc), the capacitors are placed in parallel with inductors (chokes) so that the magnet system can operate with a biased sine-wave excitation. The primary focus of the modeling effort is to analyze the electrical properties of this magnet power system.

The second operating mode of the LEB is to cycle at 1 Hz as a ramped proton synchrotron, with flat ($di/dt = 0$) "front porches" and "tops" for injection and extraction (Fig. 5.17). This 1-Hz mode is accomplished by driving the magnet system with silicon controlled rectifier (SCR) power supplies using predetermined waveforms.

We analyzed both the 10-Hz-resonant and the 1-Hz-ramp modes using as the primary analysis tool SPICE[®] version 3E, which operates on SUN workstations.

Directed Energy Weapons Power Integration (DEWPOINT)

The goals of the Directed Energy Weapons Power Integration (DEWPOINT) program are to design

and fabricate a lightweight, state-of-the-art, space traceable, 500-kW cw rf amplifier. GTE is designing and fabricating a 1-kW solid-state hybrid amplifier module (HAM) composed of solid-state triodes (SST) and a microchannel heatsink provided by Lawrence Livermore National Laboratory. The specifications on the HAM are output power of 1-kW cw, efficiency greater than 65%, and a gain greater than 9 dB. In FY 1993, GTE will

test a submodule of the HAM that consists of four SSTs and will produce greater than 250-W cw. Upon completion of these tests, GTE will begin fabricating the required number of HAMs to build a 25-kW amplifier. Westinghouse (WEC) is responsible for designing a 500-kW solid-state amplifier using the HAMs as fundamental

building blocks. After completing this design, WEC will fabricate a 25-kW cw demonstrator that is derived from the 500-kW space-traceable amplifier. The prime power for the amplifier will be designed by Electromesh Institute in Russia. Currently, the institute is designing a hyperconducting alternator to our specification.

Fig. 5.16. Magnet modeling results showing the 10-Hz resonance mode.

Fig. 5.17. Magnet modeling results showing the 1-Hz operating mode.

Plasma Source Ion Implantation

The plasma source ion implantation (PSII) process is a new manufacturing technology being codeveloped by AT Division, P Division, X Division, and MST Division in collaboration with General Motors Corporation and the University of Wisconsin. The intent of this Cooperative Research and Development Agreement (CRADA) is to develop the PSII process on a large scale for the automotive industry. PSII is a process to tribologically alter material surfaces by immersing an object in a plasma and then attracting the ions to the object with a high negative voltage. Tribology is the study of the science of friction, wear, and corrosion. For automotive applications, these objects may be drive-train components, machine tooling, or stamping dies. As an example of the process, a metallic part might be immersed in a nitrogen plasma and pulsed at high voltage to form a nitride surface layer. The PSII process shows promise as a replacement for the wet chemical bath (plating) process, thereby eliminating the associated hazardous waste.

The AT-5 contribution is to design and develop the high-power modulator systems suitable for commercializing PSII. It is anticipated that the first production-line prototype PSII systems will require peak switching currents of 200 A or more at the 150-kV levels with a few percent duty factor (0.5 to 1 MW average). Further modulator and power system development is required to commercialize full-scale automotive assembly-line processing. These rep-rated systems may operate at kilo-ampere pulse currents at the 500-kV levels. A simplified diagram of the first modulator system is shown in Fig. 5.18. A view of the hardware (Fig. 5.19) shows a striking similarity to the GTA rf modulator. It is important to note that the switching technology used for this system is a direct technology spin-off from the Strategic Defense Initiative Organization and GTA programs.

Fig. 5.18. Block diagram of PSII high-voltage modulator.

Fig. 5.19. Initial construction of PSII modulator (Ralph Cordova, AT-5).

Gyrotron

AT-5 is working with MST-4 to commercialize a Ukrainian technology that involves processing materials with directed millimeter-wave radiation. The effort is a result of a CRADA between LANL and the National Center for Manufacturing Sciences (NCMS). The CRADA involves taking a material-processing experimental stand from the Ukraine, rebuilding it to meet US safety standards and quality expectations, and providing an experimental

facility where US or Canadian members of NCMS can evaluate applications of the technology. The material processing stand consists of (1) an 84-GHz, 35-kW, cw gyrotron with a mode converter to take the overmoded output of the gyrotron and convert it to a concentrated distribution suitable for use in the processing chamber; (2) a superconducting magnet for gyrotron operation; (3) a quasi-optical transport system to duct the gyrotron radiation to a processing chamber; and (4) a processing chamber where the experimental

work takes place. This method of processing is being considered for ceramics bonding, enamel applications, Si and GaAs wafer processing, polymer hardening, and many other applications. AT-5 has received the gyrotron equipment from the Ukraine and is awaiting funding to refurbish the equipment. The system is expected to be operational 9 months from the receipt of funding. The Ukraine's operational system is shown in Fig. 5.20.

Fig. 5.20. Gyrotron-based materials processing system installed in the Ukraine.

Accelerator Production of Tritium (APT)

AT Division has been working for several years on a proposal to produce tritium with a high-energy, cw, proton accelerator. An accelerator-based approach to produce tritium offers environmental and safety advantages over a nuclear reactor. In addition, an accelerator is more easily scaled in both design and operation for reduced levels of tritium production. AT-5 has been directly involved in this proposal effort because the rf power required is so enormous. The present design requires close to 300 MW of cw rf power. At optimistic efficiencies, this would require more than 500 MW of prime power.

AT-5 has been working on the conceptual design of the Accelerator Production of Tritium (APT) rf system, including the rf power generator type, the distribution system, the power conditioning, and component protection. A large part of the effort is based on maximizing the system availability. Studies of existing systems are in progress, including the Clinton P. Anderson Meson Physics Facility (LAMPF), Continuous Beam Accelerator Facility (CEBAF), European Center for Nuclear Research (CERN), Large Electron-Positron Collider (LEP), and others.

Additionally, AT-5 has been working on the APT system design of the beam/cavity control. High-efficiency operation implies minimal control margin, but minimal control margin implies reduced control response. Tradeoffs must be considered. APT is a very heavily beam-loaded accelerator and will require excellent control to reduce beam losses. Various schemes combining both feedback and feedforward are being considered to meet the control requirements while maximizing operating efficiency.

Accelerator Transmutation of Waste (ATW) and Accelerator Based Conversion (ABC)

The Accelerator Transmutation of Waste (ATW) and the Accelerator Based Conversion (ABC) of plutonium are additional applications of the high-power proton accelerator technology being considered for APT. Design studies are taking place for all these applications, as funding permits.

The generator of choice for all these applications remains the klystron, but we have learned that the 1-MW CERN klystrons have had several failures, and their life is about 25,000 hours, on average. Reliability concerns also limit the high-frequency power per klystron to 1.0-MW cw. The vendors have improved the 352-MHz, 1.0-MW klystron to 1.3 MW, and they can now make 1.0-MW at 77 kV, but this lowers the efficiency to 62%. Thus, at 350 or 400 MHz, we can expect klystrons with 1.3-MW output power. However, we have learned that the main cause of downtime is not the klystron, but the cables and connectors, which require considerable attention for maximum system reliability.

Another generator under consideration for these applications is the klystrode because of its improved operating efficiency. The klystrode for the Chalk River Laboratory (CRL) in Canada worked very well and has produced over 70% dc-to-rf efficiency under a wide variety of conditions (compared to only 68% for the klystron, and then only under optimum conditions). The CRL klystrode is rated at 250 kW at 267 MHz.

We presented our ideas on the Accelerator Based Conversion (ABC) rf system to the Russian designers at a Los Alamos meeting, and they presented their ideas based on their use of the regotron (another type of high-power rf generator). Although the differences in approach are great, we have corresponded with our Russian counterparts to better understand each other's ideas.

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Introduction

Group AT-7 provides theoretical and computational support for AT-Division programs and supports free-electron-laser (FEL) activities within AT-Division. We conduct theoretical analysis and develop computational tools applicable to accelerator technology, including activities by the Los Alamos Accelerator Code Group (LAACG) and theoretical research in the accelerator area. AT-7 manages FEL experiments by coordinating work of contributing groups and by providing technical guidance to the FEL program offices for proposals, program directions, and external collaborative arrangements. We engage in extensive research and development on accelerator components and systems pertaining to the enhancement of FEL performance.

Free-Electron-Laser Developments

APEX

A Boeing/Los Alamos collaboration is under way to build a high-average power FEL called the Average Power Laser Experiment (APLE). The goal of APLE is to demonstrate that a FEL can produce laser light with an average power of 100 kW. A collaborative effort by many Los Alamos National Laboratory (LANL) groups has resulted in the APLE Prototype EXperiment (APEX). The APEX's purpose is to demonstrate the basic physics and technology of APLE at low-duty factor. The APEX FEL is driven by a 40-MeV electron accelerator that consists of a 1.3-GHz, /2-mode coupled-cavity linac with a 6-MeV photoinjector. The microbunch characteristics include a current of 0-300 A and a pulse FWHM of 7-15 ps. Following the commissioning of APEX in FY 1991, the FY 1992 effort focused on physics experiments associated with the FEL operation. Highlights included lasing at a wavelength of 837 nm, the shortest to date for a Los Alamos FEL. Ultrahigh current

densities of 7000 A/cm² were demonstrated from the APEX photocathode, which significantly exceeded the previously reported values for multialkali photocathodes. The electron beam's brightness at the end of the APEX 40-MeV accelerator was measured to be 3×10^{12} A/(m-rad)² at a current of 135 A, making the APEX beam one of the world's brightest high-current electron beams. Single-bunch transverse wakefield effects were measured directly for the first time using a fast streak-camera technique, and a scheme for mitigating wakefield effects in a high-current accelerator was developed. A Detailed report of APEX activities can be found in the APLE Free-Electron Laser Program section of this report.

AFEL Experiment

The Advanced Free-Electron-Laser (AFEL) experiment is a research and development initiative to advance the FEL technology required to build a compact, robust, and user-friendly system for industry. AFEL develops technology in key areas such as the high-brightness beam, high-efficiency microwiggler, high-power optical system, and user-facility.

The AFEL system, now fully assembled, consists of a high-brightness electron linac with a photoelectron source, an emittance-preserving beamline with permanent-magnet transport elements, and a high-efficiency

FEL resonator with a permanent-magnet wiggler. The linac was conditioned with high-temperature bake and glow discharge to achieve an operating vacuum of 1×10^{-9} torr. It was high-power tested to 10 MW. Since early summer, the linac has reliably generated high-brightness electron beams. Using a 1-kW drive laser, the highest peak current we obtained was 200 A, and the highest current density was 1 kA/cm². At this current level, the beam energy was around 16 MeV. The macropulse transverse emittance (normalized and rms) and energy spread were measured at 5 mm mrad and 1%. After all the beam transport elements were installed and tested, we were able to transport 70% of this beam through a tube 25-cm long and 2-mm in diameter. The permanent-magnet wiggler was assembled, tested, and field corrected. The peak magnetic field was 5 kG, corresponding to an a_w of 0.45 required for near-infrared operation. Lasing with the AFEL system is expected in early 1993. A detailed report of the AFEL activities can be found in the Advanced Free-Electron Laser Initiative section of this report.

Microwiggler

The microwiggler program's purpose was to investigate the pulsed-current microwiggler's potential to greatly reduce the electron-beam energy required to reach short wavelength. We completed the physics design and are now developing an integrated engineering design (Fig. 6.1). The engineering

Fig. 6.1. An engineering design of the pulsed-current microwiggler.

design shows a uniform wiggler field created by a pulsed current of 35 kA on a tube 305-mm long with an inner diameter of 2 mm. The uniformity required for the wiggler field leads to submicron alignment tolerance required by the slotted tube. In this engineering design, special attention has been focused on eliminating field errors and selecting construction materials. The field errors include static dipole and quadrupole errors in the body and at the ends of the wiggler. We measured and corrected these errors using the pulsed-wire technique (Fig. 6.2). In addition, we developed a field-correction system to produce time-dependent dipole and quadrupole fields in the wiggler. These fields will compensate for changes in the error fields caused by thermal heating over the macropulse duration. The materials were chosen to provide good structural stability and good vacuum. This engineering design is now being tested in the proof-of-principle (POP) experiment.

POP Experiment

By the late 1990s, the United States' microelectronics industry will be required to have an advanced set of lithography tools that will enhance its competitiveness and support a position of leadership and sufficiency in defense and consumer electronics. Los Alamos is proposing to extend the traditional optical lithography process with FELs as powerful and tunable light sources of extreme ultraviolet (XUV) radiation to produce gigabit integrated circuits with features of 0.15 μm and less.

A POP experiment is being carried out at the APEX facility. The goal of the experiment is to lase with a microwiggler at a fundamental wavelength of 850 nm and then at the third harmonics of 250 nm. The POP experiment is an extremely challenging experiment for many reasons. First, the microwigglers are 305-mm long tubing with a 2- to 3-mm inner diameter. For the electron beam to traverse such a

tube without loss requires a stable high-quality beam. We completed an experiment that showed the bright electron beam at APEX could pass through such a device with better than 90% transmission. Second, the small-signal gain and detuning range are small because of the short wavelength. The cavity length has to be controlled to 1 μm , a sensitivity that is 100 times more stringent than our previous experiments. To solve this problem, we preset the cavity length by lasing at a longer wavelength or by using the drive laser. Mirrors that have high reflectivity at two different wavelengths were specially fabricated for this purpose. Third, the pulsed-current microwiggler is used to enhance FEL gain at short wavelength with available electron-beam energy. The microwiggler is a recently developed device whose characteristics remain to be fully understood.

The good response of the photomultiplier at short wavelengths allows us to

measure the spontaneous emission and to use it as a diagnostic tool. We conducted a series of experiments to understand the measured spontaneous emission. However, we have yet to be successful in lasing. The problems encountered are caused mainly by the microwiggler's unknown properties, which include field errors and nonuniformity, heating effects, and vacuum property of material used. A third version of the microwiggler is being built and will be tested in January 1993.

Fig. 6.2. Experimental setup for measuring the field uniformity of a pulsed-current microwiggler.

Theory and Simulation

Theory

We developed software and analytical tools for several related projects: accelerator production of tritium (APT), accelerator transmutation of waste (ATW), and accelerator-based-fusion materials testing in collaboration with the Japan Atomic Energy Research Institute (JAERI). All these projects require a high-current proton or neutron linac with very low-beam loss. In FY 1991, AT-7 personnel analyzed the beam rms equations for such systems and developed software for performing rms simulations and for finding matched beams, including the effects of acceleration, nonideal quadrupole focusing, realistic gap fields, and rms space charge. This software was used along with TRACE-3D and PARMILA in support of the JAERI collaboration and is expected to be useful in all the projects described above.

We also studied beam halo formation and subsequent beamline interception. Our work on beam-halo growth began with the APT project, which showed how to create exactly stable nonlinear symplectic maps. However, the examples given were purely mathematical and not of practical interest. If realistic maps were found, we could build high-intensity linacs or large, colliding beam-storage rings with the appropriate nonlinear magnets that would ensure nonlinear stability (extremely small particle loss). Recent work has concentrated on stabilizing real maps that might be of interest for high-intensity linacs. Maps from very realistic models have been stabilized in an ideal sense. One important realization was that stability can be achieved without changing the linear or the first order nonlinear terms. Thus, in a circular machine, for example, one could achieve stability without changing the tunes of the chromaticity correction.

AT-7 has also examined the applicability of the Panofsky-Wenzel theorem of standing-wave deflectors excited in

hybrid (TE-TM mixed) modes. In their 1956 paper, Panofsky and Wenzel say they restricted their work to beams moving through cavities excited in TE or TM modes. We reexamined their work and showed the following given their assumptions: (1) the particles are rigid enough that the particle orbit is not substantially affected in its passage through the cavity, and (2) the transverse electric field vanishes at each end of the cavity, then they have implicitly derived a result that is not restricted to TE and TM modes. More specifically, the transverse momentum imparted to a charged particle moving in the z direction through a resonant cavity of length d is given by

$$\Delta p_{\perp} = \frac{e}{\omega_0} \int_0^d (-i) \nabla_{\perp} E_z dz$$

where e is the charge of the particle, ω_0 is the angular frequency and $\nabla_{\perp} E_z$ is the transverse gradient of the z component of the electric field along the path of the particle. This more general result gave valuable insight into the study of a proposed deflector for APT.

We analyzed the effect of transversely rotated quadrupoles mixing the transverse phase spaces. Assuming that the initial phase spaces are uncorrelated, we have shown that there is an emittance growth in both planes of

$$\Delta \epsilon^2 = \frac{\sin^2 2\theta}{f^2} \sigma_{11} \sigma_{33}$$

where the quadrupole of focal length f is rotated by an angle θ transversely. σ_{11} and σ_{33} are beam sigma-matrix elements.

Simulations

The APEX beamline has been simulated extensively. We have calculated the effects from transverse wakefields (confirmed by actual measurements shown in Fig. 6.3), transversely rotated quadrupoles, and virtual cathode formation just off the photocathode. We have also carefully simulated the emittance-measurement techniques and have determined that for electron

beams from photoinjectors, typical emittance-measurement techniques (e.g., quadrupole scans or multiple screens) consistently underestimate the emittance. The error can be as large as a factor of 2 to 4 resulting from the nonthermal electron distribution. The unfortunate side effect is that it is now more difficult to match electron beams into various beamline elements, such as bends or wigglers that require explicit knowledge of the beam's phase space.

Our collaborations with Boeing have contributed to the APLE beamline design. We developed simulation tools to model the actual nonsymmetric magnetic field in the APLE-injector experiment by including direct Biot-Savart integration of the current in PARMELA. Using this tool, we corrected the field errors by carefully using transverse stacks of permanent

Fig. 6.3. Time-resolved horizontal beam site at screen (a) without transverse wakefields, (b) with transverse wakefields.

magnets. In addition, we used PARMELA to design the beamline and to demonstrate the match into the bends and the wiggler. We also performed beam-interception calculations in the wiggler to ensure that the power interception is acceptable, and three-dimensional field simulations on the APLE cavities to determine the field asymmetry from the cavity drive slots and power losses.

AT-7 has designed and simulated a 70-MeV beamline for plane-based FEL applications. We accelerate a 5 nC, 20 ps bunch to 40 MeV at which point it is bunched in a chicane buncher to 800 A. The bunch is accelerated another 30 MeV to a total of 70 MeV. After matching this beam to a wiggler, FELEX simulations showed up to 20% energy extraction from this bunch.

We designed a postaccelerated RKA (Fig. 6.4) with the simulation tools developed for the relativistic klystron amplifier (RKA). We have learned that the maximum harmonic current modulation from bunching within a cavity as a function of the space charge has two peaks: one when the beam is ballistic and a second, larger one, when the beam is close to the space charge limit. The fundamental harmonic current can be as much as 1.6 times the average current at the second peak. In this regime, most of the beam's initial energy is captured in the beam's potential fields. We discovered that by including an idler cavity, the higher harmonics (i.e., second and third) have nearly the same current as the fundamental. For short pulse lengths (around 100 ns), the electron beam's Coulomb fields can be short circuited in the output cavity. This allows us to bunch close to the space charge limit and obtain the high-harmonic current, but yet still have

efficient power extraction. For longer pulse lengths (beyond 1 ms), the electron beam cannot be shorted out, and the beam energy in the potential fields is lost. However, if the beam is postaccelerated after bunching, the high-harmonic current is preserved and all the additional power added to the bunch can be extracted, resulting in high-overall efficiency. This device has both higher harmonic currents and significantly shorter lengths than a single diode RKA with the same beam current and total voltage. We also noted that this device could be used to extract efficiently at the third, and possibly higher, harmonics and could compete with other sources at 11.4 GHz in regards to size, power, and efficiency.

Fig. 6.4. Particle-in-all simulation of a post-accelerated relativistic klystron.

(a)

(b)

Fig. 6.5. (a) A1W deflector modeled by MAFIA, (b) Electric field plot produced by MAFIA postprocessor.

MAFIA postprocessors DIFF, FIELDS, and POWER were written as tools for the MAFIA user (Fig. 6.5). Program DIFF subtracts the electric and magnetic fields of one MAFIA run from another, allowing the user to see the effect of a perturbation. Program FIELDS interpolates the MAFIA calculated electric and magnetic fields in between mesh locations and allows for easier interface with particle-pushing codes. Program POWER computes stored energy, total power loss due to finite conductivity, individual power loss for each metal, and power-loss densities for the metals specified by the user. These codes were used in the analyses of the APLE design, the APEX linac, and the deflecting cavity studied for APT.

The electron-pushing code PARMELA has been ported to the UNICOS machines, and the various versions of PARMELA have been combined into a unified version. This new code includes both external POISSON and MAFIA fields and three-dimensional injector solenoid fields created by Biot-Savart's integration of current loops.

Previously, a code to simulate beam-beam effect in the strong-strong regime was developed using moment methods and was shown to be very fast. The limitations of the code were that it was only a two-dimensional code and that an accelerator ring was modeled only as a linear device. These restrictions have recently been removed. The new beam-beam code for strong-strong regime simulations includes three-dimensional effects, such as synchrotron resonances due to finite crossing angle and the interaction of the beam-beam nonlinearities with the machine's nonlinearities. In addition, tracer particles have been added for purposes of visualization.

Los Alamos Accelerator Code Group

Funded by the Department of Energy to serve the US scientific community, the LAACG provides software and services to design and analyze particle accelerators and beam-transport systems. Its main activities include developing and maintaining software; consulting with others; distributing software and documentation; and gathering and disseminating information. In recent years, the code group's services have extended to international users.

Software Development and Maintenance

The LAACG completed two major revisions to the widely used POISSON/SUPERFISH codes used to design accelerator components, including magnets and radio-frequency (rf) cavities. The first major revision was Release 3, which contained bug fixes, physics enhancements, and expanded graphics support. The second major revision, Release 4, included removing all bit packing, increasing FORTRAN-77 standardization, including the pre-processor FRONT, improving graphics capability based on the X-Windows protocol, and producing arrow plots

(Fig. 6.6). Release 4 is available for various platforms, including Sun SPARC, HP Series 700, IBM RISC/6000, SGI, VAX/VMS, and Cray/UNICOS.

The LAACG expanded its activities related to ARGUS, a three-dimensional family of simulation codes developed at Science Application International Corporation (SAIC). ARGUS contains modules for steady-state and time-dependent particle-in-cell simulations and for time domain and frequency domain electromagnetic simulations. Code group personnel have used ARGUS to model the Large Orbit Gyrotron experiment. They also attended a course at SAIC to become expert users and to provide SAIC with guidance in preparing the 1993 release of ARGUS through the LAACG. Figure 6.7 shows an example of ARGUS output.

During FY 1992 Cray computers at Los Alamos and the National Energy Research Supercomputer Center (NERSC) at Livermore switched to the UNICOS operating system. Code group personnel developed UNICOS versions of several programs, including MAFIA 2.04 and PARMILA. In addition, code group personnel began using the

INGRID mesh generator as a first step toward performing simulation with unstructured grids.

User Consultation

The LAACG consulted with many researchers at national laboratories, universities, and in industry. Most consultation involved helping researchers correctly use codes to perform calculations and simulations.

Distribution of Software and Documentation

The LAACG distributes software in three ways: electronic transmission, magnetic media (tapes), and access to software at NERSC. The LAACG also distributes documentation. From January to June 1992, the LAACG delivered software to over 150 contacts (including system managers) and mailed out over 900 documents. These figures increased dramatically in the latter half of 1992 because of widespread interest in POISSON/SUPERFISH Release 4.

Fig. 6.6. Arrow plot of field calculated with SUPERFISH codes.

Gathering and Dissemination of Information

During the 1992 Linear Accelerator Conference at Ottawa, Canada, the code group organized an information booth to introduce code group services to users. In addition, it held a "town meeting" to hear users' concerns regarding accelerator code development and availability. The LAACG is now co-organizing the 1993 Computational Accelerator Physics Conference, which will be held in February 1993.

Other Activities

Alpha Simulation Using Neutral Beams

Effects such as instabilities or anomalous transport from the alpha particles produced in burning plasmas may affect the performance of ignited fusion machines such as ITER. It is important to obtain information about these effects soon so the best designs for these future machines can be produced. Experimental simulation has been done in existing devices by injecting neutral 250-KeV beams with scaled magnetic fields. However, we

realized that neutral beams developed for the neutral particle beam (NPB) program could provide much more realistic experimental simulations of the possible effects at conditions much closer to fusion conditions. Before we discovered the usefulness of the neutral particle beam, a cw 1.7 MeV D- beam with a current of 125 mA in one module was needed, and another 4 to 16 modules were required to inject approximately the same free-energy density into a device, such as TFTR or DIII-D, at full-magnetic field under near-fusion conditions as would be produced in a burning plasma. Single modules with these parameters are being developed for the NPB program.

XUV Plasma Source

We are seeking funding for a unique electron beam-driven plasma XUV source that is currently in conceptual development. The source consists of a 5-MeV electron beam and a tenuous plasma of neon or nitrogen. The electron beam is a continuous stream of pairs of electron bunches. The first bunch has low charge and is 10 ps long; it partially ionizes the gas into plasma. The second bunch has a high charge of 5 nC and is less than 1 ps long; it will deposit 75% of its energy into the plasma via wakefield interaction. The resulting hot, dense plasma quickly (i.e., within 100 ps) loses energy by XUV line radiation. The output wavelength depends upon the chosen gas type and its pressure. The output power level depends upon the gas type and the parameters of the input electron beam. Compared with similar schemes for example, the laser-driven plasma, this scheme has several advantages. First, an rf electron beam avoids the particulate contaminants of a laser produced plasma. Second, plasma recombination to its initial atomic state allows the gas to be recycled through a closed-loop recovery system. Third, it is "granular" (i.e., acceptably small unit size and cost) enough to be of interest to soft x-ray lithography systems. Fourth, this approach is adjustable to yield short (15 nm) or long (60 nm)

Fig. 6.7. Typical output from the ARGUS code.

wavelength irradiance by changing only the composition of the flowing gas (e.g., neon versus nitrogen). This operation's versatility is an attribute not offered before to the semiconductor manufacturing industry. Fifth, this design has multisided output access, each yielding irradiance suitable to illuminate a single stepper. Sixth, this source has upgrade power potential because the injector-accelerator structure does not have an operational thermal limit.

SSC Collaboration

Our collaboration with the Superconducting Super Collider (SSC) theory group concentrates on the rf counter phasing and beam-loading stability problems for the low energy booster (LEB). To avoid multipacting in the rf cavities, the cavity voltage must be above 20 kV. However, to achieve the desired capture during injection, the rf voltage must be about 10 kV. To avoid this problem, we plan to counter-phase the rf cavities, 50%. Consequently, the cavities can be run above the multipacting limit, yet the injection capture can still be optimum. In addition, the cavities can be easily rephased when higher voltage is needed. We have shown that if the rf amplifier can deliver 120 kW per cavity, there will be enough rf power to maintain the correct voltage when the tuning error in the cavities is moderate. Higher harmonic rf systems are used in synchrotrons and storage rings to increase the bunch length and the spread of the synchrotron frequency to reduce the space charge effect and to dampen the longitudinal instabilities. We also examined the beam-loading stability in an rf system with a higher harmonic by directly investigating the equations derived from the equivalent-circuit model. The stability conditions for the LEB have been derived from the linearized equations.

PSR Development

We observed a fast transverse instability with beam loss in the 800-MeV Los Alamos proton storage ring when the injected beam intensity reached 3×10^{13} protons per pulse. Understanding this instability and the methods to control it have taken on new importance as the neutron scattering community considers the next generation of accelerator-driven spallation neutron sources, which call for peak proton intensities of 2×10^{14} per pulse or higher. Previous observations indicate that the instability is probably driven by electrons trapped within the proton beam. Theoretical study has shown that beam leakage in the interbunch gap leads to electron trapping. In 1992, several experiments were carried out by using the newly implemented "pinger" and by varying the machine transition gamma to explore further the nature of the "e-p" instability. Currently, we are examining the experimental data and writing a simulation program to study the longitudinal space-charge effects.

LANSCÉ II Proposal

Recently, serious consideration has been given to a next-generation accelerator-driven spallation neutron source at Los Alamos. Conceptual design is in process. We helped design the lattices for the 800-MeV ring and the 2-GeV ring, provided the preliminary stability studies, and studied the design's longitudinal phase-space painting scheme.

ESNIT Collaboration

The Energy Selective Neutron Irradiation Testing project is a joint venture between LANL and JAERI. An accelerated deuterium beam is directed to a lithium target, producing neutrons used for fusion materials research. Currently, we are considering a 2- to 3-MeV RFQ at either 120 MHz or 175 MHz, with a 75- to 125-mA deuterium beam, followed by a 35- to 40-MeV DTL.

Accelerator Theory Notes

The following AT-7 Accelerator Theory Notes were distributed during the report period:

1. M. J. Browman, "Testing Program Power," AT-7:92-ATN-1.
2. M. J. Browman, "Effect of Tuning Stubs on the Power Loss in a Four Slot Cavity," AT-7:92-ATN-2.
3. M. J. Browman, "Generating MAFIA Azimuthally Symmetric Cavities from a Two-dimensional Cross Section," AT-7:92-ATN-3.
4. R. Ryne, "Normal Analysis of Anharmonic Oscillator, including Envelope and Emittance Growth Calculations," AT-7:92-ATN-4
5. R. Gluckstern/R. Copper, "Beam Breakup Estimates for a Super Conducting Proton LINAC," AT-7:92-ATN-5.
6. R. Gluckstern, "Transient Effects in the Slotted Cylinder," AT-7:92-ATN-6.
7. C. Fortgang, "Field Correction for a One-metered Long Permanent-Magnet Wiggler," AT-7:92-ATN-7.
8. J. Merson, "Power Densities for Superconducting RFQ LY-10-14," AT-7:92-ATN-8.
9. J. Merson, "HALAST and GMHALD on UNICOS," AT-7:92-ATN-9.
10. J. Merson, "SPCG 4 and GRAF on UNICOS," AT-7:92-ATN-10.
11. T. Wang, "Robinson Instability with a Higher RF Harmonic," AT-7:92-ATN-11.
12. M. J. Browman, "The Panofsky - Wenzel Theorem Revisited," AT-7:92-ATN-12.

Technical Memoranda

1. J. Merson, "Cell Dimensions used to Generate SFDATA Table for ATW 350 DTL," AT-7:92-TM-1.
2. M. J. Browman, "Program Plots," AT-7:92-TM-2.
3. M. J. Browman, "Program Power," AT-7:92-TM-3.
4. J. Merson, "Dimensions of Superconducting RFQ LY-7-7," AT-7:92-TM-4.
5. J. Merson, "Prior work done on Behavior of Multiple Beams in an RFQ," AT-7:92-TM-6.
6. J. Merson, Wangler, "Superconducting RFQ LY-7-15 Dimensions," AT-7:92-TM-7.
7. J. Merson, "Power Densities and Fields for Superconducting RFQ LY-7-15," AT-7:92-TM-8.

8. J. Merson, "Total Power Loss for Superconducting RFQ LY-7-15," AT-7:92-TM-9.
9. J. Merson, Wangler, "Dimensions of Superconducting RFQ LY-8-7," AT-7:92-TM-10.
10. J. Merson, "Power Densities for Superconducting RFQ LY-8-7," AT-7:92-TM-11.
11. J. Merson, "Frequency, a Stored Energy and Vane Voltage of LY-8-7 from MAFIA Superconducting RFQ," AT-7:92-TM-12.
12. J. Merson, "Fields at End Wall of LY-8-7," AT-7:92-TM-13.
13. J. Merson, "Superfish Definition and Results for Superconducting RFQ SCRFQ 11," AT-7:92-TM-15.
14. H. Takeda, "Optimization of APLE Photoinjector with the Injector Solenoid Field Modeled by the Biot-Savart Law," AT-7:92-TM-16.
15. H. Takeda, "Optimization of ESNIT RFQ at 175 MHz," AT-7:92-TM-17.
16. J. Merson, "End Region Dimensions," AT-7:92-TM-18.
17. J. Merson, "Field's for Superconducting RFQ Geometry ZY5-AJ," AT-7:91-TM-24.
18. J. Merson, "Summary of Super Conducting RFQ Mafia Calculations," AT-7:91-TM-25.
19. M. J. Browman, "Comparison Between Previously used Side-complined Geometry and APEX Cavity," AT-7:91-TM-26.
20. M. J. Browman/Rodenz, "Proposed Changes to M3," AT-7:91-TM-27.
21. M. J. Browman, "PARMELA Input for APLE Cavities with Different Plot Configurations," AT-7:91-TM-28.
22. M. J. Browman, "Effect of Tuners on the Fields in an APLE Cavity," AT-7:91-TM-29.
23. J. Merson, "NERSE Unicos Class Highlights," AT-7:91-TM-30.
24. A. Lombardi, "Wakefields Effect in Microwiggler," AT-7:91-TM-31.
25. J. Merson, "Source of SF Data used for Current ATW PARMILA Calculations," AT-7:91-TM-32.
26. J. Merson, "Preliminary ATW DTL Dimensions," AT-7:91-TM-33.
27. J. Merson, "POISSON/SUPERFISH Mafia and NERSC," AT-7:91-TM-34.
28. J. Merson, "Power Density in Selected Cells of ATW DTL 350d," AT-7:91-TM-35.
29. J. Merson, "Power Requirements Dimensions of ATW 350 DTL," AT-7:91-TM-36.

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Introduction

In FY 1992, AT-8's major efforts included producing, installing, and commissioning of the control system for the intertank matching section (IMS) and the first drift tube linac (DTL) section of the Ground Test Accelerator (GTA). Typically, AT-8's tasks are to generate the hardware and software necessary to control and monitor accelerator components and subsystems, then to integrate, and test the controls on the beamline.

Background

Two experiments which studied the performance of the IMS and DTL were executed. During these experiments, controls personnel manned two shifts a day to assist with accelerator operation and data acquisition. The distributed architecture control system for the experiments consisted of about 15 front-end VME-based INPUT/OUTPUT controllers (IOCs) with associated instrumentation, and approximately 10 color work stations used as operator interfaces running the EPICS software.

This year marked the first use of the GTA control room. Previous experiments had been operated from a temporary control room amidst the electronic equipment racks. Operating from the control room was a definitive test of control system reliability and functionality, as neither the accelerator nor electronic equipment could be observed directly.

Accelerator Control

We installed the first DTL in a new vacuum vessel that is planned to contain five DTL modules. The control system monitors and provides supervisory control for the vacuum, cryogenic temperature, radio-frequency (rf) power, DTL tank positioners, frequency tuners, and a steering magnet. An additional three IOCs were installed to accommodate new DTL controls, rf controls, and beam diagnostics instrumentation.

We installed a complete vacuum control system for the new DTL vessel. Pumps, gauges, and valves are all operable through the control system as well as from a manual control panel. The control system provides interlocks that can automatically shut off devices or close valves in the event of an equipment failure. The control system also provides automatic trending of vacuum readings. A single IOC provides control and monitoring of the radio-frequency quadrupole (RFQ) vacuum system and the first DTL vacuum system.

The DTL, like the RFQ, operates at cryogenic temperatures. A large number of silicon diode temperature transducers are used to monitor the temperature of the DTL structure and various points along the cryogenic manifolds. Temperature readings are automatically logged by the control system. The desired operating set-point is typically 25 to 35 K. If the control system detects any temperatures above 50 K, it automatically disables beam production.

The DTL module is supported by five mechanical positioners, much like the RFQ. This enables the structure to be translated along orthogonal axes after the accelerator has cooled to cryogenic temperatures. These positioners are operable from the control room, which transforms the operator's desired x/y coordinates into position commands for each of the five positioners.

We installed another rf power system controller for driving the DTL. The control system interface is nearly identical to the ones installed previously for the RFQ and IMS. Through the control system, the operator may set and monitor parameters such as phase and amplitude for any cavity. RF engineers may control more detailed settings such as system calibrations and closed-loop control coefficients.

Operations

Integration and operation have become important issues as hardware is added to GTA and experiments have become more complicated. New application software and some hardware have been customized to assist in operating the accelerator effectively and safely.

The accelerator safety systems now include a control system integrity check. As part of the integrity check, the run-permit system monitors a 'heartbeat' from each IOC that controls critical accelerator operations. If any of these front-end processors fails to respond or is operating abnormally the accelerator is automatically shut down. The control system can also disable the accelerator when other abnormal conditions are detected, such as a vacuum reading that is too high or steering magnets that are not set within tolerance.

We endeavored to create software tools that aid experiments in effective and efficient accelerator control. The data archiving software has been tailored to users' requests. A new capability has been developed that can automatically vary an accelerator parameter through a series of set-points and collect data at each set-point, resulting in increased efficiency over repeated manual adjustments and data acquisition. A data retrieval tool extracts previously archived data and provides plotting, translation to several foreign computer file formats, and statistical analysis. Other tools include an on-line operator log, an alarm manager that provides orderly notification of anomalies, and a graphic timing control program that displays accelerator timing settings as a timing logic diagram.

Waveform Acquisition

We now use a digitizer that has the capability to acquire synchronous waveforms. This digitizer was installed and a software driver was written to capture waveforms of various accelerator signals at a sample rate of 5 MHz with 12-bit resolution. The entire macropulse can be captured, and up to approximately 80 contiguous macropulses can be buffered in the IOC. Four channels are captured simultaneously and time-stamped so they can be later correlated with other data. The operator can set the number of samples per waveform, the number of waveforms to acquire, and the trigger timing. The operator can also preview the four waveforms on the work station before data is acquired. We used this system during experiment 2A for collecting data for beam jitter studies and for studying the performance of rf adaptive feed-forward electronics.

Off-line Testing

We maintained two test stands for testing accelerator structures before they were installed on the GTA. A low-power cryogenic test bed and a similar facility for high-power testing have been instrumented with controls equipment to duplicate beam-line conditions. Besides providing data on the behavior and operation of the devices under test, we developed and tested control algorithms before installing them in the GTA control system.

Commissioning and Automation Software Tools

Several tools that have specific roles in the commissioning of the accelerator were either implemented this year or were considerably changed from last year. These include programs for phase scan, for steering in the low-energy beam transport (LEBT) and IMS, and for automating rf cavity conditioning. A program was also developed that recorded beam position data and transferred it across the network to a

VAX system for use by RESOLVE, a beam-tracing program. In addition, the program ESCAN was ported from the GTA control system to the discharge test stand (DTS) control system. This brought all the emittance scanning programs to one method allowing for more meaningful comparison.

Phase Scan

The phase scan program that we began testing last year was brought to the point of full functionality and maturity and is robust enough to operate effectively. It does automatic scanning, data scaling, data display, and data storage under operator control. We modified the original design because the rf power occasionally shut down at zero phase, and a specified time period was required for the motorized phase shifter to work after a command to shift phase had been sent. Now the data that an operator sets to configure the scan is saved, on a cavity by cavity basis, for a default setup the next time the program is run. This program has produced essential data for documenting operation of the cavities as well as for initial tuning of the cavities.

Steering

AT-8 built a beam-steering software tool that will aid us in our studies of beam launching into the first DTL tank. This tool provides the beam with a target at the DTL entrance; the target consists of position and angle in x and y. This beam-steering tool has yet to be used on-line because of inconsistencies with calibration data from the IMS microstrip probes that provide data to the steering tool. The steering tool for LEBT steering, previously reported, uses a similar philosophy of steering to a target. We dramatically modified that code because the LEBT had been shortened. Lamberton magnets now located inside the solenoids are employed to do the steering. However, inconsistent experimental data obtained from emittance scanners in the LEBT have prohibited this program from being

fully tested. We expect the problems to be understood and corrected and the program to be operational in a very short time.

Automatic rf Structure Conditioning

We implemented a software tool to provide automatic rf conditioning of the RFQ, our first attempt at automated conditioning for any GTA cavity. The tool was partially tested during the last beam experiment, but a complete test requires full access to the RFQ. We hope this effort will yield information useful in designing a general code to condition all GTA cavities.

Video Beam Profiles

The video profile diagnostic system implemented for GTA in FY 1992 was brought to a fully operational state after several problems were overcome. We discovered there was not enough residual gas to produce light, thus gas needed to be injected into the beam path. The first attempt at this uncovered faults in the electronics package that controlled the injection valve, in the software that controlled that valve, and in the hardware that delivered the gas. Modifications were made and the system became operational. Initially, only the system designer could operate the diagnostic. However, we modified the software interface to become more user friendly, and now this diagnostic is a production tool that can be used by any GTA operator.

Another problem encountered was the early images captured by the video profile showed background that extended beyond the edges of the actual viewing area. We used several methods to eliminate this background. We reduced the intensifier gain and integrated over only the time when beam is present to reduce the background to an acceptable level. A cross section of the remaining image was modeled by a linear combination of two Gaussian functions. The narrower function was the image from the beam interaction, therefore, we calculated centroids and

widths from that information while the wider function compensated for the background. This calculation was incorporated into the real-time imaging software and displayed as the images were obtained.

Presentations were made on this diagnostic at both the Neutral Particle Beam (NPB) Symposium at Argonne and the LINAC Conference at Ottawa. These presentations covered both the implementation system and data analysis methods.

Ion Source Automation

In FY 1992, AT-8 demonstrated a neural-network based automated ion-source tuner could control the small-angle source on the Discharge Test Stand. This work has since been transferred to the GTA injector control system. Although the problem of automating this source is quite similar to the work done on the DTS, there are major differences. First, the dimensionality of the problem is increased because there are more adjustable parameters that must be addressed on the 4X source used on GTA. Second, the increased mass of the GTA source requires more heat for proper arc operation than did the SAS source. In fact, the heaters provided on the 4X source are insufficient to bring the anode and cathode to proper operating temperature, so the extra heat required must be provided by the arc itself. Therefore, the control of the temperatures of the anode and cathode must follow a different strategy. Third, to move the ion-source controller from a demonstration mode to an operational mode requires manual operation. When the controller is operational it must operate unattended and therefore must be robust. However, we have resolved all problems identified while using the controller in the DTS demonstration. For example, if a thermocouple indicates an impossible temperature, the controller reacts by taking the loop off-line but maintains the heater set-point. This open-loop mode of operation can continue for a short time allowing the operator to

address the problem. The system is robust to problems with the thermocouples, the errors in the Allen-Bradley computer interface, and in an automatic to manual mode change. The ion source is maintained at operational because of the system's sensitivity to these conditions and the controller's reaction to the problems.

During FY 1992 we presented our work on automation to an industrial workshop organized by SDIO, at the NPB Symposium at Argonne, at the LINAC Conference in Ottawa, and we published our work in *Nuclear Instruments and Methods*.

Control System Hardware

Operational Support

Final checkout and integration of all beam experiment IC controls were in progress at the beginning of FY 1992. During the early stages of the experiment, it became clear that additional controls and monitors were necessary for several components of the IMS. We designed additional hardware for the rf-drive-loop elbows to maintain the temperatures and to prevent rf field breakdown, for the frequency tuner step-motors to prevent binding at cryogenic temperature, and for the upstream steering quadrupole motors to facilitate operation within acceptable limits. The original drive motor on the D-plate bending magnet was found to be marginal in torque; therefore, controls for a larger motor were added. The control room timing system, which provided key timing signals for control room data acquisition, and the IMS video profile system were integrated and became solid operational tools.

To prepare for experiment 2A and future experiments, we implemented two test beds so that each of the ten DTL modules could be characterized, rf-conditioned, and functionally tested before installation on the beamline. Each DTL module contained 34 temperature monitors, 2 rf frequency tuners, and 2 step motors for two-

dimensional steering-quadrupole positioning. DTL module 1 also implements five step motors for three-dimensional positioning of the entire module. We decided to upgrade the control system for the High-Power Cryogenic Test Bed (HPCTB), to a system that could be capable of high-power rf conditioning of DTL modules. This modification, in conjunction with required safety enhancements, necessitated a complete revamping of control wiring and electronics. Another IOC and associated controls were fabricated and integrated for use with the Low-Power Cryogenic Test Bed (LPCTB).

Before experiment 2A, the beamline controls for DTL module 1 were fabricated. Wiring to the beamline was installed and tested, and a new DTL IOC was implemented on the classified control network. After DTL positioning tests, we determined that larger step motors with linear variable differential transducer (LVDT) positional feedback would be required for adequate DTL position control. Consequently, we installed and tested additional hardware.

For experiment 2A, both DTL module 1 and the D-1 diagnostic plate were installed in the first of two DTL vacuum vessels. A rack of equipment with its associated cabling was installed to control the various valves, pumps, and monitors for this new vacuum system. The new controls were interfaced to the existing vacuum control IOC.

Because high-beam energies and currents were associated with experiment 2D, we used sophisticated beam-loss monitoring electronics to determine when beam was spilled. A new IOC was assembled to interface with prototype beam-loss electronics so that it could be functionally tested during experiment 2A. The new IOC contains approximately 100 channels of binary and analog inputs and outputs as well as time-stamp generation, triggering, and fast-protect signals. A large database, several sequence programs, and control screens were also implemented to support this effort.

Several modifications to the versa-module European (VME) time-stamp generation modules were made after experiment 1C for compliance with new low-level rf timing requirements for experiments 2A. The new time-stamping hardware was fabricated and installed in all eight GTA IOC's that incorporated hardware-generated time stamps and performed as required during the experiment.

Fast-Protect System Development

To protect accelerator components at higher beam energies, we implemented a fast-reacting hardware fault detection system for experiment 2A that can truncate a beam pulse within microseconds of a fault. The hardware designed for this system included several new modules. The Fast-Protect Master module (Fig. 7.1) generates a carrier signal that is daisy chained to a series of slave modules. Any slave module receiving a fault input will not pass the carrier signal, thereby breaking the chain. At the end of the chain is the Extractor Gate Interface Chassis. The chassis has inputs from the Personnel Safety System, the Run-Permit System, and the Shift Supervisor Key as well as from Fast-Protect. Inputs from any of these systems can terminate the GTA beam. Under program control, the Fast-Protect Master module can be

used to perform a series of functional tests of the entire Fast-Protect System. Each slave module can be monitored by the control system to determine the status of its inputs. Versions of the slave module were designed in a VME package for beam-loss applications and in a VME External Interface (VXI) package for rf applications. Fast-Protect Warning Modules were also designed and built for use with the beam-loss monitor electronics to alert operators when the amount of spilled beam was approaching the level at which the beam would be truncated. Software drivers for each of these devices were written, and the entire system was demonstrated successfully on experiment 2A.

Optically Isolated Binary Output Module

Some GTA injector reliability problems persisted as a result of electro-magnetic interference noise-induced failures of the Allen-Bradley modules used to control the high-voltage dome electronics. We determined that the Allen-Bradley contact output modules (Model OW) were the most likely cause of the problem. Consequently, replacement modules with high-electrical isolation were designed, built, and installed. No further reliability problems associated with injector controls were encountered.

Step-Motor Control

AT-8 incorporated a convenient scheme design into the existing motor driver backplane electronics for controlling brakes on step motor assemblies (e.g., the offset beamline harp assemblies and high-energy beam transport [HEBT] variable-field quadrupoles).

A new version of the motor driver backplane has been designed to support four motors with incremental encoders. This version will be required for HEBT motor control. A compatible VME transition board has also been designed.

Transient Digitizer

Transient digitizers with analog bandwidths of up to 10 MHz are needed and the demand is expected to increase for experiment 2D. Currently, only the Joerger model VTR-1 transient recorders have been used routinely on GTA, and the 8-bit resolution of these units is not sufficient for several applications, including beam jitter and rf feed-forward control studies. This year Omnibyte, Inc. began manufacturing a four-channel, 5 MS/s, 12-bit module designed by FERMI Laboratory for a very attractive price. We purchased and evaluated one of these modules and concluded that although it suffers from digital noise pickup in the board's analog front end, which limits usable resolution to about 10 bits, the module was found to be an attractive alternative to the VTR-1 in most respects, including a much lower cost per-channel.

Next Generation Computer for IOCs

The Motorola MVME-167 central processing unit module was evaluated as an alternative for the aging Heurikon HKV2FA units we presently use. The 167 incorporates many important advantages including a 68040 processor, on-board ethernet interface, less heat susceptibility and larger EPROM and RAM capacity. The 167 processor runs control applications at 6 to 10 times the speed of the HKV2FA and costs about 25% less to field in a typical application.

Fig. 7.1. Fast-Protect System.

We purchased the support software for this new board and converted four test IOCs to use the 167 so that future control system applications can be developed and tested with the 167 instead of the HKV2FA.

Binary Output

The Xycom XY240 VME binary output module was thoroughly evaluated as a possible replacement for the XY220. The 240 was found to be a superior module and a recommended replacement for future applications. We wrote a software driver to allow this module to be incorporated into the EPICS control system.

Nonvolatile IOC Memory Module

A Force RR-2 VME memory module was fitted with 2 MB of SRAM and an onboard battery for backup. A file system was created and the board was configured as a RAM disk. Such a configuration may be used for future applications that require a completely self-contained IOC running with no network resources or with operating parameters that must be maintained even if there is a power outage.

Electronic Computer Aided Design (ECAD) Support

The Electronic Computer Aided Design (ECAD) effort included supporting AT-3's diagnostics design requirements, AT-5's low-level and high-power rf design requirements, and AT-8's controls hardware development requirements. Most of this support effort was directed toward designing printed circuit boards and associated hardware to meet these requirements. In FY 1992, we placed 80 printed circuit board fabrication orders, amounting to more than 850 boards delivered.

ECAD also increased design efforts in the area of mechanical packaging and documentation. This included the layout and design of low-level VME EXTended INTerface, (VXI) printed circuit board module, and submodule assemblies.

VXI mechanical module templates were developed in Autocad to aid in the documentation of each type.

We increased our extensive, customized parts library for printed circuit board design and our documentation for a variety of parts. This customized parts library ensures consistency in design among many ECAD designers and supplies useful and relevant information for the parts list extraction process. Parts lists extracted from each design include a parts description, reference designation, manufacturer's part number, and manufacturer's name.

Computing Support

The AT Division computing network supports exceptionally diverse computer equipment and applications. AT-8's computing support section is responsible for operating and maintaining the division's network. Using modern, but proven technology, this section strives to maintain high-quality network services in a heterogeneous computing environment containing over 150 work stations, over 150 personal computers (IBM and Macintosh), approximately 20 VAX computers, and several network file servers. The services range across two open, unclassified networks and two classified networks. Extensive network equipment, including bridges, routers, and terminal servers, are used throughout the network, and network statistics are collected at a central location. The computing support section is also responsible for complying with various Laboratory and Department of Energy policies and orders for open and classified computing.

AT Division networks support a wide spectrum of scientific computing, including measurement and control systems, software development, mechanical computer aided design (CAD), electronic CAD, experimental data reduction, and system modeling. Resources such as printers and plotters are shared among users, and the electronic mail services for all computers are integrated throughout the open network

and with the Laboratory's Integrated Computing Network (ICN). Open standards—TCP/IP, DECNET, X-Windows, NFS, NIS, and DNS for example—are used when possible. As in the past, the reliability of the network and availability of central services has steadily improved, consequently, AT-Division network is a model for others in the Laboratory.

During FY 1992, a major effort was made to consolidate computer services for the VAX computers and Sun workstations, resulting in reduced costs for support and maintenance, improved reliability, and increased performance. For instance, the original 6 VAX clusters with 28 VAX computers were consolidated into 3 clusters and 17 computers, resulting in an annual savings of approximately \$50K in hardware maintenance, while maintaining the same computer power. Similar upgrades to the Sun file servers on the open network resulted in comparable savings. We also added mail service and central file backup capability to the personal computers.

AT-8's computing support section surveyed the division members to determine the requirements for database management. From this survey, we determined that a client/server model relational database management system (RDBMS) would meet the division's requirements. We evaluated potential commercial RDBMS and made preliminary recommendations to the division.

AT-9 Very High-Power Microwave Sources and Effects

RB92-078 014

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Introduction

AT-9 is the Very High-Power Microwave Sources and Effects Group within Los Alamos National Laboratory (LANL). The group's mission is to develop new high-power microwave (HPM) generators and apply them to Department of Energy (DOE) and Department of Defense (DoD) problems. The AT-9 efforts span the range from studying the basic physics of high-current electron beam propagation to the application of HPM to industry. The common theme among these projects is very high-peak power microwave radiation. These high peak powers lead to interesting physics as well as to challenging engineering in most of our work. The group's projects are divided into two broad categories with some overlap: microwave source technology development and microwave source technology application. Major applications for HPM are defense (electromagnetic countermeasures), radio frequency sources for particle accelerators such as the proposed Next Linear Collider (NLC), advanced radar, and industrial uses such as coal processing to minimize waste products.

Background

AT-9 was originally founded to investigate the defense implications and applications of HPM and transient-pulse technology. From its inception, our group has had a two-pronged approach of investigating how to produce HPM with our microwave-source development work, as well as how to apply HPM technology. The applied work began with electronics vulnerability testing to quantify susceptibility against microwave radiation. This has evolved into an extensive test program, both at LANL and at large transient electromagnetic simulation facilities elsewhere. AT-9 has been involved in transient-pulse technology as well, developing transmitters, antennas, and diagnostics that have been used for radar and vulnerability testing.

Fiscal year 1992 has been successful for AT-9. One of our teams received the Laboratory's Distinguished Performance award for experimentally testing and demonstrating a single-shot microwave-source concept in record time. We have made substantial progress on both the large-orbit gyrokystron and relativistic klystron amplifier (RKA) projects, with 400-MW output power measured in the RKA work. AT-9 has worked to get the Advanced Free-Electron Laser (AFEL) on the air and has performed extensive Vulnerability, Lethality, and Effects (VLE) testing; new initiatives have begun on both defense and industrial projects. Funding for AT-9 activities is supplied by a variety of DOE and DoD sponsors. Within the DOE, our funding supports science (large-orbit gyrotron [LOG] and RKA), hardness testing, cleanup (ground penetrating radar (GPR) and microwave coal beneficiation), and participation in the AFEL. The DoD sponsors include the Army, Air Force and Navy.

Microwave Source Development

The NLC is a proposed linear accelerator that is to be built after the Superconducting Super Collider (SSC) is completed. This machine will allow energetic electron collisions to be studied at much higher energies than currently possible at Stanford Linear Collider (SLC) and LEP at CERN. The accelerator will require many gigawatts of peak microwave power to accelerate the particles. To minimize cost, the rf power sources must be of very high peak power with high frequency (1-20 GHz) and high reliability. These ambitious goals require major advances in microwave tube technology ranging from the electron gun and cathode . . . to the optics of intense space-charged beams . . . to the nonlinear interactions involved in bunching the beam, to the high-power output couplers and windows.

The military requirement for HPM remains strong even after the recent changes in the world military picture. Sophisticated, sensitive electronics are pervasive on the modern battlefield. HPM has a role in the give-and-take between these electronics and the countermeasures employed against them. The defense requirements for HPM sources encompass the NLC needs, but are more diverse. Some defense applications are single shot, others are tunable, while others may be transient, wideband pulses. AT-9 is currently investigating the LOG and the RKA. Each source concept has strengths that make it useful for both scientific and military application.

Relativistic Klystron Amplifier

Los Alamos is developing an L-band high-current RKA. Although present experiments are single pulse, the long-term goal is to achieve 1 kJ/pulse with repetitive pulse capability at a repetition rate of 5 Hz with a longer-term goal of 100 Hz. The RKA has an input cavity, a single idler cavity, and an output cavity (Fig. 8.1). The buncher section, which consists of the input and idler cavities, has been experimentally tested and is performing as designed. We designed the buncher section by using particle-in-cell (PIC) code calculations with the Los Alamos code ISIS. PIC code modeling has proved to be very important for successful design because of the highly nonlinear nature of the RKA caused by the intense space-charge effects. The most recent efforts involved adding the output cavity to the tube and experimentally optimizing the output power and pulse length to reach the design goal of 1 kJ/pulse. A number of expected problems that have been encountered with the output cavity are being systematically addressed. Problems include rf breakdown in the cavity and the ability to match the beam impedance to cavity gap shunt impedance for the most efficient conversion of beam power to microwave radiation.

The electron beam is formed from a 6.2-cm-diameter annular field-emission cathode and is slightly compressed by a converging 0.5 T axial magnetic field to a nominally 5.9-cm-diameter beam with a 5-mm thickness. The typical beam voltage is 620 kV with an increasing current of 3-6 kA. The input and idler cavities are quarter-wave coaxial resonators. The input cavity is coupled to a 300-kW L-band magnetron through an iris into a tapered, reduced-height WR-650 waveguide. The idler cavity has an annular tuning ring which gives flexibility in inductively tuning the cavity. The output cavity, a noseless pillbox resonator with an annular coupling slot near the outer diameter, couples power into a low-impedance coaxial transmission

line. The coax tapers out into standard 6 inch 50 line in which power is measured with a directional coupler and then dissipated in a dummy load.

The input cavity was changed from a loop coupling design in the original RKA to a waveguide input with iris coupling to accommodate the increase in drive power from 5 kW to a maximum of 300 kW (Fig. 8.2).

The coupling iris is large enough for the input cavity to behave as a matched load when the beam is present in the gap. Consequently, the cavity is very mismatched and reflects most of the incident rf power before the beam current turns on. Then as the beam traverses the gap, the cavity is nearly

matched, and most of the magnetron drive power is absorbed and transferred to modulate the beam. We confirmed the low reflection with beam loading by computer modeling. The comparison between theory and experiment is quite good and is shown in Fig. 8.3.

According to PIC code calculations, the amount of current modulation produced by the input cavity, necessary for full-power output of the tube, was about 10%. As shown in Fig. 8.4, the input cavity is easily capable of producing 10% modulation with only 200 kW of injected rf power.

Fig. 8.1. Schematic drawing of relativistic klystron amplifier.

Fig. 8.2. RKA input cavity design.

Fig. 8.3. Theoretical (lower) and experimental power reflected at the input cavity.

We modified the original RKA idler cavity to include a tuning ring so the cavity could be inductively tuned (the cavity's resonant frequency is higher than the modulation frequency). This allowed for greater beam current modulation at the output of the idler cavity for the same amount of bunched beam at the input. Once the cavity was installed on the beamline, data were taken for different tuning frequencies and input cavity drive powers to find the best combination for maximum beam modulation. Figure 8.5 shows the good input match during the pulse, as well as an output power of more than 100 MW.

Using PIC code simulations, we determined the maximum output of modulated current from the idler cavity to be 65% to 75%. Figure 8.5 shows the good input match during the pulse, as well as an output power of more than 100 MW. The average beam modulation is near 66% over the pulse length. The amount of extractable beam power is usually given as $P = (V \cdot I_b)/2$. For this case, about 1 GW of extractable energy is available at the fundamental frequency. The output cavity should be at least 70% efficient and should produce 700 MW of rf power out or 700 J per pulse.

Fig. 8.5. Data for Shot #1196 showing good match of input, as well as > 100-MW output power.

Power from the initial output cavity design was significantly less than expected. One difficulty with the modeling was that a 2D code was used to calculate the interaction, which does not realistically model the three dimensional geometry of the actual experiment. Even though the designed Q of the cavity was 10, the measured cavity Q was approximately 200 and therefore could not be tuned on resonance for maximum efficiency without producing electric fields that exceeded the level for rf breakdown.

After a number of shots at three different input power settings, no consistent rf output pulses were seen. Upon disassembly, the cavity was found to be arcing at the vanes used to adjust the coupling. Once most of the vanes were machined away, the first sign of linear operation started to appear. For 5 kW of injected rf power, output power was an average 6 MW. For 20 kW of injected power, output power was an average of 25 MW. In addition, the rf pulse length increased to over a microsecond, which was our goal.

Fig 8.4. Current modulation downstream of input cavity as a function of rf input power.

A new section of the output cavity has been built based on cold tests that give the desired loaded Q of ~10. The much lower loaded Q results in much lower electric fields across the cavity gap thereby mitigating the breakdown problem. This change creates a better match between the beam impedance and the cavity shunt impedance resulting in maximum conversion efficiency from beam power to microwave power.

Injection powers of 6, 20, and 90 kW have been tried with some success. At the lower injection powers, the RKA was showing approximately 30 decibel (dB) of gain, giving output powers of 6 and 20 MW, respectively. With 90 kW of injected power, the RKA appears to have four distinct modes of operation.

The first mode is one in which not much power is produced even though most of the waveforms are essentially good. The idler cavity signal is taken from a B-dot in the cavity. As can be seen in Fig. 8.6, the cavity signal stays at a relatively low value throughout the pulse for no apparent reason. Output power is usually in the range of 20 to 40 MW for 0.5 μ s.

In the second mode, the idler cavity shows reasonable modulation at the very beginning, but then falls off abruptly after about 300 ns. This waveform usually correlates with the beam voltage changes at the beginning of electron emission from the cathode, but an initial bump in the beam voltage does not always produce the same problem in the idler. Output power typically spikes to about 20 to 50 MW.

The third mode consists of the idler cavity modulating well for the first half of the pulse, but then something seems to change the beam modulation at the input cavity. This, in turn, causes a change in the input cavity match and increases the amount of reflected injection power. With the drive power to the input cavity dropping, the desired beam modulation also drops off and drops the output power. Often, the beginning of the idler cavity drop correlates with the beginning of the beam voltage's descent. Output power is reasonable in these shots and very often from 80 to 130 MW for 0.5 μ s.

In the fourth and final mode, the idler cavity works well. The output power climbs to the point where the output cavity gap field is high enough to reflect electrons back up stream. Consequently, the idler cavity breaks down and ends the pulse, usually only 350 ns from the initial start. Average output

power ranges from 200 to 300 MW over the ramp-shaped pulse with peak power levels as high as 400 MW. The gain in this mode is about 36 dB. In the main part of the pulse, there are 110J of rf energy.

If the fourth mode could be chosen selectively, the breakdown might be solved by lowering further the output cavity Q, thus reducing the gap fields and also modifying the idler cavity to handle higher fields without breaking down. However, only the third mode gives output powers that are consistent with the gains measured at low power injections. Solving this problem is difficult, because there are no data to correlate directly with the problem to date. The breakdown could be a result of the changing beam voltage affecting the way the input cavity bunches. Alternatively, higher beam harmonics could be propagating up the beam pipe creating the mismatch in the input cavity.

Large Orbit Gyrotron

We have designed and are testing a LOG amplifier for 1.3 GHz operation in 65 ns pulses. The ultimate power output goal is 500 MW with a gain of at least 20 dB. This initial investigation is intended to lay the groundwork for operation at 11.4 GHz for particle accelerator applications and also at frequencies of up to 35 GHz for other uses. Computational design has been performed with the resonant cavity code MAFIA and the PIC codes MERLIN and ISIS. Experimental measurements of the resonator modes were correlated with computational and analytical predictions. We studied and experimentally verified electron-beam optics through a magnetic cusp with ISIS and MERLIN to develop a suitable electron-beam trajectory from the electron gun into the microwave resonator region. Performance tests have begun. In its final form, the device will use two resonators separated by an electron-beam drift tube.

Fig. 8.6. Data for Shot #1146, showing peak output power of 400 MW and pulse energy >100 joules.

A LOG amplifier operating at 1.3 GHz is being developed to operate at powers of up to 500 MW for 65 ns pulses. While this initial investigation is being performed at 1.3 GHz, this amplifier can be scaled to higher frequencies in a straightforward fashion. LOG oscillators have operated at 15 GHz and higher frequencies with comparable performance at lower frequencies. Amplifier operation has been examined theoretically and experimentally, but less extensively.

These LOG amplifiers produce microwaves when a helically rotating electron beam interacts with the oscillating fields of a resonant cavity structure. The electron beam is formed by injecting a hollow, nonrotating beam, born in an axial magnetic field, through a magnetic cusp positioned at the anode plane. The gyrotron radius of the electron is equal to the radius of the annular beam, so this device is referred to as "large-orbit," as opposed to a conventional gyrotron in which the orbits may be very small because of a relatively high magnetic field. An annular slot is cut into the iron cusp plate to allow the beam to pass into the downstream resonator. In the cusp, a portion of the axial beam energy is converted to rotational energy. Typical ratios of rotational velocity to axial velocity (defined as α) are in the range of 1.5 to 2.5. The electron beam entering the resonator has an energy of 500 to 700 keV, a current of 1 to 3 kA, and a radius of 5 to 8 cm. The device, shown in Fig. 8.7, employs a cylindrical resonator with three vanes in the wall spaced equally in azimuth.

The amplifier is designed to have two cylindrical resonators as described above. The vane structure is used to evoke coupling of the rotating electron beam with the transverse electric $TE(0,1,n)$ resonant cavity mode of the cylindrical structure by modifying the normally circular electric field pattern of the mode into a scalloped pattern, similar to the $TE(3,1,n)$ mode but near the lower $TE(0,1,n)$ resonant frequency for a nonvaned cylindrical wall with an intermediate radius.

We used two loops, one in each of the two vanes, to feed rf into the cavity. If the beam's angular velocity is synchronized, the cavity's standing wave pattern will couple to the rotating beam provided. Consequently, an azimuthal density perturbation will grow on the beam with three-density maxima around the azimuth. The magnitude of the density variation will grow as the beam propagates down the resonator's length, influenced by the applied oscillating rf fields and the space-charge self-fields that drive the negative mass instability. The instability will grow as the electron beam propagates through the system. Feedback from the beam instability drives the cavity fields to greater amplitude.

The first cavity's downstream end has a central opening that forms the entrance to a cylindrical, nonvaned electron-beam drift pipe. The pipe isolates the rf radiation between the first and second cavities and serves as a region where the beam bunching can grow by the negative mass instability, independent of applied microwave fields. An optimum drift pipe length will be determined experimentally to maximize

azimuthal beam bunching. To extract energy, a second output resonator designed to be strongly coupled to the beam will be placed downstream of the drift pipe at the point of optimum beam bunching. Mode converters suitable for transforming the TE_{01} circular waveguide mode of the output resonator into TE_{10} rectangular waveguide mode have been thoroughly studied since the 1950s.

We designed the electron gun and optimized the electron beam trajectory using the two-dimensional versions of ISIS and MERLIN PIC codes. Preliminary studies were performed with a computational technique known as synthesis. This technique steps the particles backward in position and time from the final state, (i.e., beam current, position, and velocity components). The initial conditions (i.e., emission-electrode position, shape, and potential) that lead to the final state, and a satisfactory trajectory through the device can be determined.

Fig. 8.7. Schematic drawing of large-orbit gyrokystron amplifier.

An acceptable synthetically generated diode configuration consists of a cathode-emission annulus with a diameter of 14 to 14.2 cm on a conical equipotential surface at an angle of 67.5° with respect to the symmetry axis (Fig. 8.8). The distance between the emission annulus and the anode was 2.2 cm, yielding a cathode electric field of 300 kV/cm at a voltage of 650 kV. The annular opening at the anode through which the beam passes into the resonator drift section has a mean diameter of 12.5 cm and a width of 1 cm.

We began with a synthetic computation that was the starting point to conventionally calculate beam dynamics moving forward in time. A conventional run using the diode and drift-pipe parameters from the synthetic calculations agreed with the synthetic calculation prediction. All of the current emitted from the cathode, up to a maximum of 2.7 kA passed through the cusp and drifted with little radial oscillation while in the resonator region.

We built the diode hardware using PIC modeling; the experimental diode

geometry is shown in Fig. 8.9. Electron emission was produced from an annular region of the angled surface either by mounting a knife-edged ring or a velvet belt on the surface as an explosive emission cathode. The emitting ring's diameter varied from 11.4 to 14 cm. The drift pipe had no vane structure for these diode experiments, to approximate the conditions of the computer model.

Alpha, (α) was measured using a quartz witness plate placed in the beam path. The quartz's luminosity permits a pattern of the electron deposition to be seen at the plate location. A shadow is cast on the quartz when a metal rectangle is attached upright on

Fig. 8.9. Three-dimensional ISIS calculation of electron trajectories including dc and ac fields.

Fig. 8.8. Electron gun and beam optics synthesized using computer modeling.

the upstream side of the quartz at the radius of the beam. The ratio of the length of the shadow to the height of the obstruction is a measurement of α .

Alpha was measured to be in the range of 1.5 to 2.0 for a magnetic field of 400 G and in the range of 2.0 to 2.5 with a magnetic field strength of 500 G. This alpha range most accurately matched that shown by the computer model as providing good beam transport.

We transported 3 kA past the cusp with an alpha of 1.5 using a knife-edge emitter with a diameter of 12.4 cm, a magnetic field of 300 to 400 G and a diode voltage of 700 kV. Waveforms for this case are shown in Fig. 8.10. These lower magnetic field conditions are those anticipated for the 1.3 GHz amplifier experiments. The computer study did not include these parameters in its investigation, but rather used magnetic field of 500 G at the cathode, based upon the needs of an amplifier designed for higher frequency.

We conducted an extensive study of the resonant structure's cavity modes using the electromagnetic field-solving code MAFIA, analytic modeling, and cold-test measurements performed with a vector network analyzer. Figure 8.11 shows the frequencies measured with a network analyzer connected to magnetic loop probes in the cavity, oriented to couple to the $TE(0,1,n)$ modes. The peak of interest, the $TE(0,1,0.5)$ mode, oscillates at 1,280 Hz. Figure 8.12 shows the MAFIA calculated electric-field pattern for this mode at 1277 MHz, showing good agreement with the cold-test measurement. When we test the input cavity with the downstream end fully open, the cavity had a Q of 45. As a two-stage device, the first stage Q will be much higher, of the order of several hundred. The output cavity Q of the two-stage device will be similar to that of the single-stage resonator, in the range of 25 to 100.

The experimental configuration consists of the diode, magnetic field coils, downstream resonator section, and a dielectric vacuum window. The vacuum window is used for radiating the microwaves into an anechoic volume downstream of the vacuum chamber. A 4-kW 1.3-GHz source provides rf input drive to the resonator in these initial studies. Up to 20 MW is available as input drive, but device modifications are required for aperture coupling to accommodate the power. Presently, magnetic loops are located at the base of two vanes for cavity input drive. A loop in the third vane is used to monitor the cavity's standing-wave field. A stub-waveguide receiver is positioned in the anechoic volume, downstream of the opened end of the resonator to monitor the radiated power.

Fig. 8.10. Beam voltage and current from a typical gyrotron shot. Input beam power to gyrotron is 2.4 GW.

Fig. 8.11. Measured mode spectrum of gyrotron resonant structure. The strong peak at 1286 MHz is the desired operating point.

Fig. 8.12. MAFIA output showing electric field distribution of 3-field symmetric mode at 1277 MHz.

We evaluate amplifier performance by comparing the radiated microwave power in three different circumstances. First, the radiated power resulting from the 4-kW input drive alone is measured. Second, we measure the radiated power with no input drive, but with the electron beam injected. Finally, the radiated power is measured when both input rf drive and injected electron beam are present in the resonator. Relative power measurements among shots are performed by comparing detected signals received with a waveguide stub placed at a fixed location in the far field downstream of the resonator.

With no input drive, the radiated rf power pulse was narrow in time, 42-ns long, with a wide statistical standard deviation of 24 ns or 56%. This duration is significantly less (approximately 65 ns) than the full width at half maximum (FWHM) duration of the electron-beam current in the resonator. In addition, the mean value of the peak power, while larger than with input drive, had a 28% standard deviation. With input drive, the output power pulse continued for 60 ns, nearly the length of the electron beam pulse, with a standard deviation of 16 ns or 27%. The peak power of the output pulse using input drive was 26% lower than without input drive, but was longer by 50% with a smaller standard deviation of 16 ns or 27%. The FWHM of the fast Fourier transform of the rf signal was 36 MHz (25 MHz standard deviation) without input drive and 27 MHz (17 MHz standard deviation) with input drive. Hence, there was clear improvement in the output power pulse associated with the application of input rf drive, as was shown in total energy of the output pulse, the frequency purity, and in reduction of the statistical variation among pulses.

Piezoelectric Experiments

Compact sources of high-intensity electromagnetic radiation offer important advantages in counter-electronic military applications. At DoD's request, AT-9 and several other Laboratory groups developed a new concept and conducted simple, proof-of-principle (POP) field experiments for producing a compact source of intense microwave radiation. These experiments demonstrated that microwave radiation is produced from piezoelectric material when it is compressed by a high-explosive-generated shock wave. This is the first time microwave radiation has been produced directly from a high explosive without the complex, intermediate stage, which consists of a magnetic flux compression-generator power supply that produces a high-intensity electron beam, which is subsequently converted to microwaves. This entire effort from concept through explosive testing was conducted in approximately 2 weeks. The group received the Laboratory's Distinguished Performance Award in recognition of its efforts.

Explosively-driven microwave and ultra wideband generators can produce mission kill of electronic equipment at stand-off ranges, preventing blast damage (or combined explosive and electromagnetic effects at closer ranges if desired). These systems can be delivered to close range by existing missile and artillery systems. Explosively-powered devices would enable much smaller payloads to exist, requiring much smaller delivery systems, thereby allowing a much wider range of uses.

A piezoelectric material becomes electrically polarized when mechanically deformed, or it changes dimension when placed in an electric field. Historically these materials have been crystalline such as quartz or ceramic. However, recent developments with organic polymers have resulted in materials with far greater piezo activity than any other synthetic or natural

polymer. This newer material is a flexible, compliant, clear plastic film that can be readily cut, shaped, and metalized with a conductive electrode coating. The properties of interest are

- wide frequency range-near dc to low GHz
- vast dynamic-range-sensitive to both minute forces and explosive shocks (nanobar to megabar)
- high-output voltage-10 times higher than piezoceramic for the same input force
- high-dc dielectric strength-75 V/ μ m
- high-mechanical strength and impact resistance
- very low raw material and fabrication costs
- reasonable dielectric constant (relative dielectric constant ~ 12) enabling a high stored energy

One characteristic of a high-explosive detonation is the intense shock wave that generates very high pressures in the 300 to 500 kbar range and as high as 1 Mbar in a convergent lens system. The high pressure in conjunction with a piezoelectric material enables large voltages and currents to be generated. Piezoelectric plastic film can produce electric fields of 0.3 V/m per Pascal. Because 0.1 Mbar ($= 10^{10}$ Pa) is easily achievable with a high-explosive detonation, we can generate electric fields of 3×10^9 V/m assuming linear induced voltage vs pressure behavior of the material. This is a reasonable assumption based on the manufacturer's specifications and on Sandia's work with piezoelectric material in an unrelated application. Electric fields of, 3×10^9 V/m exceed the dc dielectric strength, which is about 10^8 V/m. It is well known that as pulse length decreases the dielectric breakdown level increases, so that as the pulse length is reduced from dc to fractions of a microsecond, the breakdown level will increase significantly above the dc dielectric strength of 10^8 V/m. For comparison, the electric field produced by nuclear electromagnetic pulse (EMP) is 10^5 V/m. The piezoelectric material can also be treated as a

current generator. A 1 mm² sample of piezoelectric material has generated 8 A of current, indicating that if the size were scaled to 7 x 7 cm, more than 5 kA could be generated. When scaled to realistic sizes, these numbers show that piezoelectric material could produce electromagnetic pulses that could be radiated and used against a variety of targets.

Piezoelectric material is available in films 9 to 800 μ m thick with a thin 0.2 μ m aluminum coating sputtered onto both sides for electrical contact. The film layers can be stacked so the voltage across one thickness adds to the voltage of the other thicknesses, such as when capacitors are connected in series. This piezoelectric material should be configured such that an explosive shock wave can compress the material, and with a geometry which allows connection to an antenna. We performed a POP experiment to become more familiar with the concepts that might lend to a useful device.

Although performed quickly, simply, and with unrefined diagnostics, the POP field tests demonstrated conclusively that electromagnetic radiation can be generated by piezoelectric material when a high-explosive driven shock wave is used to compress the material. The two configurations shown in Figs. 8.13 and 8.14 were tested at Firing Point 6 in Ancho Canyon in a collaborative experiment with AT-9 and M-6, the Shock Wave Physics Group; MEE-3, the Instrumentation Group; MEE-9, and the Engineering Design Group. The configuration in Fig. 8.13 illustrates that when we stack the layers of piezoelectric film, voltage is generated across the layers. A wideband bowtop antenna was used to radiate the energy. Physical dimensions of the film were 5 x 5 cm; 10 layers of 52- μ m thick film were stacked one on top of the other. This configuration used 300 g of Detasheet high explosive in two 4-mm-thick, 7 x 7 cm squares. The test configuration shown in Fig. 8.14 used a single 0.5-mm-thick sheet of piezoelectric polymer. This configuration uses the

material's capability to generate a large current to drive a loop antenna designed to resonate at 50 MHz.

Diagnostics employed at the firing point included five antennas covering overlapping frequency bands that ranged from a few megahertz to 12 GHz. The antennas included a horizontal longwire doublet, a log periodic antenna (bandwidth = 20 MHz to 1 GHz), two ridged waveguide horns with different bandwidths (0.5 to 6 GHz and 1.0 to 12.4 GHz), and a D-dot probe (electrically small dipole). We observed radiation at frequencies ranging from a few megahertz to as high as 0.5 to 1 GHz when the bowtop antenna with a 30 to 700 MHz bandwidth was used to radiate the pulse. We observed rise times of approximately 3 ns and pulse widths as long as

600 ns in the detected microwave signals. Figure 8.15 shows data from two different receiving antennas on the same explosive shot, when we used the Fig. 8.13 bowtop geometry. We estimated the radiated power densities at the antennas located 40 feet from the firing table to be tens of μ W/cm².

Based on all five shots in two vastly different configurations (three with the bowtop and two with the loop antenna), these field tests demonstrated that electromagnetic radiation can be repeatedly generated by piezoelectric material that is compressed by a high-explosive driven shock wave. This microwave source package is relatively compact and the quantity of high explosive is only a few hundred grams.

Fig. 8.13. Explosively driven rf experimental configuration (Bowtop antenna).

MVF 91-80 1

Fig. 8.14. Explosively driven rf experimental layout (loop antenna).

Fig. 8.15. Detected output waveforms received at 40 ft from Bowtop antenna: (a) receiver passband 20-1000 MHz and (b) receiver passband .5 - 6 GHz.

Although these are our first experiments and our understanding of the physics and engineering issues involved is extremely limited, we foresee improvements of at least eight orders of magnitude in the power levels.

This team of people developed a scientific concept, engineered the concept, and implemented a proof of principle demonstration in less than 2 weeks. The successful completion of

this project on such a tight time scale, with personnel from five groups across four technical divisions, required an exemplary level of skill, teamwork, and dedication by each member well beyond normal expectations.

Pulsed-Power Research and Development

AT-9 is actively developing pulsed-power technology for advanced,

repetitively pulsed HPM sources and for wideband, transient pulse generation. These applications require outputs of tens of kilovolts to megavolts into loads of 50 to 100 ohms for nanosecond to microsecond pulse lengths at repetition rates up to tens of kilohertz. Most of our developmental pulsers employ state-of-the-art thyatron switches. These tubes are part of a long-term effort at Los Alamos to develop extremely high-powered repetitive switches for particle beams and lasers.

BANSHEE

The BANSHEE pulser currently supplies a 600-kV, 10-kA, 2-μs pulse. It is being used as the electron-beam driver for the RKA experiment and as a thyatron test bed (Fig. 8.16). Recently, the CX1812 thyatron tube produced by English Electric Valve (EEV) has been tested to failure. Currently, this thyatron tube, developed for the Strategic Defense Initiative Organization (SDIO)

Fig. 8.16. BANSHEE pulser with RKA experiment in place.

applications has the highest peak power of any thyratron produced. Several smaller tubes have been qualified at the multigigawatt, micro-second level at up to 5 Hz. EEV has corrected the flaws discovered in the first tests of the CX1812 and has produced an improved tube variant that will be tested in BANSHEE in 1993. The tests to date have reached the limits of the pulsed-power system in several areas. An improved charging system and power supply have been designed and presented to sponsors. If funded, these would allow BANSHEE to operate in burst mode at the megawatt average power level. Improved capacitors have been identified that can operate reliably at this average power level.

Portable Pulser

The portable pulser is another advanced modulator developed for HPM source experiments. In 1992 this system was moved into the new AT-9 laboratory in building MPF-14, the first step in the system's full-power commissioning. In 1993 we will add the shielding and diagnostic facilities, and the LOG experiments will be transferred to this machine, yielding a highly reproducible 600-kV, 3-kA pulse. The system's ability to reproduce voltage will be a major improvement over the existing gyrotron power source, because the voltage repeatability between shots is critical when developing the complex beam optics in the cusp-injected electron gun.

WEMPE 4

A wideband electromagnetic pulse environment (WEMPE 4) was developed by AT-9 over the past several years for effects testing, developing antennas, and developing GPR. A turnkey WEMPE 4 system was constructed and delivered to the air force's Rome Air Development Center in 1992, Fig. 8.17. This is a user-friendly package supplied for wideband EMP experiments.

Electron-Gun Test Stand

Construction has started on an electron gun test stand, a 200-kV, 200-A, 15-Hz high-voltage modulator used for developing and testing electron-gun components. We will be able to test high-current density cathodes and parts of advanced electron guns independently of the microwave source experiments on BANSHEE.

Vulnerability, Lethality, and Effects (VL&E) Testing

During the last 3 years, the Vulnerability, Lethality, and Effects (VL&E) Section in AT-9 has conducted many rf effects tests, and the quantity of work is growing every year. This section is responsible for planning, executing, and documenting electromagnetic-coupling tests for various government sponsors; data processing and analysis are an additional charter shared with Group X-5. The electromagnetic-

coupling tests provide AT-9 with the opportunity to continue to develop ultrawideband video-pulse sources and to contribute critical coupling data to national committees such as the System Effects Assessment Team, the Foreign Asset Assessment Team, and the Department Of Energy (DOE) Tri-Lab High Power Microwave (HPM) Vulnerability Committee. During FY 1992, the VL&E Section conducted electromagnetic-coupling tests on three mobile military systems. These tests used a variety of electromagnetic environments to ensure complete electromagnetic characterization of each system.

High-Level Testing of Mobile Military Systems

During FY 1992, AT-9 conducted low-level frequency-domain tests on each system to build a baseline data set from which the response of the command post to high-level environments would be predicted. A typical system is shown in Fig. 8.18. The data acquired during the high-level electromagnetic (EM) coupling test were then compared with the values predicted from the low-level data to evaluate the accuracy of numerical techniques used in generating the "pre-test prediction" values. After review of the data, we determined that the numerical techniques used to create the predicted values were valid, and we incorporated both the high- and low-level data into a transfer function data base. This data base is available to assist weapons designers in their evaluation of weapons's output in the context of the electromagnetic frequency coupling windows on that particular system. The test were conducted at the Defense Nuclear Agency's Advanced Research Electromagnetic Simulator (ARES); a facility originally built to test ICBM systems such as the MINUTEMAN and the PEACEKEEPER. However, recent modifications have given the facility the capability to conduct both low-level frequency domain and low-, medium-, and high-level time domain pulse testing.

Fig. 8.17. Electromagnetic Pulse Generator delivered to Rome Air Development Center.

Fig. 8.18. Typical electronic system undergoing EMP VLE tests.

Test Point Impedance Assessment

While the overall test methodology did not vary from that used in FY1991, we did use the tests to complete development of a simple technique used to measure the impedance of a test point *in situ*.

In the past, the HPM testing community has used an nominal value of 50 ohms (Ω) for the test point impedance. This choice is heavily derived from S_{11}

(reflected energy) measurements made on numerous test points and based on the fact that printed circuit designers use dimensions for the printed circuit that correspond to approximately 50 Ω for frequencies > 1 GHz. However, that value is not valid because the circuit components begin to dominate the circuit impedance at frequencies < 1 GHz. We believe the S_{11} technique is limited to providing insight only into the trend of the data but not the actual value. During the S_{11} measurement, the coupling path and test point impedance

are measured in parallel. However, when the system is illuminated in a free space EM environment, the coupling path and test point impedance are in series, resulting in a different voltage and current distribution as compared with the S_{11} measurement. This led us to devise a simple method by which the test engineer could determine the test point impedance in a realistic measurement situation.

Our new technique connects a shunt resistor across the test point to ground. The ground point is common to voltage probe and the test point circuit. This creates a three-resistor parallel circuit that features two known (voltage probe and shunt resistor) and one unknown (test point impedance) resistances. Figure 8.19a shows the equivalent circuit at the test point. This parallel circuit is in series with the coupling aperture. With different values of the shunt resistor, we can obtain different transfer functions. Figure 8.19b shows three such transfer functions that illustrate the change in response caused by the shunt register. By ratioing the "no shunt" case with the "1000 Ω " shunt and the "50 Ω " shunt, we can calculate the actual test point impedance at each frequency of interest. This technique is very useful because it is easy to implement and gives the test engineer an accurate measure of the effect of instrumentations on the test point response.

In FY 1993, four systems will be tested, with the first test scheduled to begin in March 1993. The systems will be tested at a variety of simulators because of the various requirements of our sponsors. The data acquired in FY 1992 will be used to improve the extrapolation techniques currently used in scaling low-level responses to high-level environments and will become the backbone of system vulnerability analysis currently underway at Los Alamos. The data will also become an important cross-check for an ongoing EM modeling effort that is studying the coupling efficiency of an incident plane wave to a complex, lossy cavity. Additional smaller effects tests will be performed in conjunction with the GPR program to continue the development of untrawideband video pulsers and appropriate antennas used to propagate the new wave forms.

High-Performance Ground Penetrating Radar (HIPERGPR)

AT-9's goal is to produce an effective subsurface radar that has commercial value for ongoing environmental cleanup programs by developing the existing prototype at LANL into a fieldable system with substantially higher performance than existing systems. This prototype has four orders of magnitude more peak power and five orders of magnitude more average power than commercial GPR units.

When combined with the proper radar receiver technology, these power increases result in the radar penetrating much deeper into the earth. The prototype high performance ground penetrating radar (HIPERGPR) has demonstrated ten times greater depth range than a commercial GPR when tested at TA-49. In FY 1992, our efforts with GPR focused on benchmarking the device's performance against realistic targets as well as improving the system's signal processing and user interface.

The concept of cradle-to-grave control of weapons materials puts new requirements on defense programs (DP) to locate buried waste and to continuously monitor disposal sites. Wideband high-power pulsers and diagnostics developed for the nuclear effects program can be used to clean up DOE waste sites effectively, efficiently, and economically. Hence, the HIPERGPR with its greater search range, can perform noninvasive, subsurface surveys over realistically sized burial sites. Additionally, the HIPERGPR provides the unique additional capability to accurately measure the burial depths.

a.

b.

Fig. 8.19. Measurement of circuit impedance: (a) circuit model showing added Z_{sh} resistor, and (b) measured coupling data showing effect of three different resistance values.

Materials Processing with High-Power Microwaves (HPM)

The application of high-power microwaves (HPM) to materials processing is a new project in AT-9 begun in 1992. Initially, we are researching how microwave radiation interacts with coal in a collaboration with the Coal Technology Office at LANL. Further work involving microwave chemistry has also begun.

Coal, the most common fossil fuel, produces pollution as a byproduct of its combustion. This major limitation to its use has led us to investigate methods of cleaning up the coal fuel cycle.

Beneficiation is the process of removing pollutants before the coal is burned. Typically, less useful constituents such as sulfur and heavy metals are removed by a chemical cleansing process. A related technique is coal gasification or liquefaction in which the most valuable constituents are removed from the bulk of the coal leaving less useful and dirtier components as waste. AT-9 is investigating the interaction of microwave pulses with coal samples in an experimental effort to understand the flow of microwave energy into the coal on a short time scale. We believe that the coal will be heated and fractured allowing the volatile constituents to be released and separated.

Our experimental investigation of the interaction of microwave pulses and coal began with low power network-analyzer measurements on coal samples. The purpose is to learn the dielectric constant and loss tangent of coal as a function of frequency and to study the variations of these parameters among different samples. The next step involves setting up the chemical diagnostics for the high-power tests.

In collaboration with CLS-4 (Photo Chemistry and Photo Physics), we evaluated various chemical analysis techniques from gas chromatography to mass spectroscopy, as well as more advanced techniques employed

routinely in CLS. For the initial work, we focused on Fourier-transform infrared spectroscopy augmented by mass spectroscopy. Infrared spectroscopy is the preferred technique for analyzing the hydrocarbon gases expected to be evolved from the coal samples. An experimental sample collection system was set up in AT-9 as a precursor to the actual microwave processing, and several samples were analyzed at CLS-6. The next step is to irradiate coal samples using the 20-MW, 1300-MHz klystron in building MPF-14. A waveguide sample holder has been assembled for this purpose and is ready for use.

Microwave heating is becoming a useful tool of the industrial chemist. Many processes are aided by the selective and rapid heating produced by microwaves. AT-9 is looking at the possible benefits of high-power pulsed microwave energy for chemistry. Many chemical reactions are limited by competing reactions that interfere with the desired reaction. However, if microwave energy is applied in a pulsed mode, the desired interaction may be favored so that the overall system efficiency is enhanced. This has been demonstrated at low-power levels, and we are trying to employ the high-power sources and expertise in AT-9 to improve technique.

Wideband Antenna Development

The antenna development work in AT-9 emphasizes broadband, high-peak power radiators for transient EMP used for wideband-VLE field testing and impulse radar. Our development goals are to maximize bandwidth and voltage breakdown capability while minimizing dispersion. The latest antenna developed is a modified ridged-waveguide transverse-electric mode structure used for GPR and supplied to Air Force and Army laboratories in 1992.

1300-MHz RF for the Advanced Free-Electron Laser

The 20-MW, 1300-MHz klystron was brought back on line to support the AFEL experiment. Many improvements were made to the system's housekeeping in the wake of the Tiger Team visit. After these improvements were completed, the waveguide was reconnected to the compact linac of the AFEL and the system was promptly conditioned up to the 20-MeV level (10 megawatts peak rf power). During 1992 klystron personnel worked closely with AT-7 personnel to commission the AFEL and diagnose and troubleshoot the beamline and subsystems. AT-9 worked closely with AT-7 and AT-5 to implement and test rf control systems on the system. The work with AT-5 was a high-power shakedown test of the University of Twente's low-level control system. This realistic test allowed for many small details to be corrected before the system was shipped to the Netherlands.

AT-9 proposed a design for a compact 1300-MHz rf system intended to be a dedicated klystron stand for the AFEL. The design is a very compact package designed to minimize the AFEL size. It will employ a large klystron, the Litton L-3702, several of which are available in AT-9. This system will supply a longer pulse with higher peak power, as well as higher average power than the existing stand, and will be completely integrated into the AFEL computer automated control system. The construction of the 1300-MHz rf system for the AFEL will be a collaborative effort between AT-5, AT-7, and AT-9 in 1993.

AT-10 GTA Installation, Commissioning, and Operations

RB92-351001

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Introduction

The primary mission of AT-10 has been to support Ground Test Accelerator (GTA) beam experiments. AT-10 is responsible for ion-injector development, final beamline installation of GTA components, and commissioning and operation of the accelerator. We perform the final radio-frequency (rf) cavity preparation, conditioning, alignment, and integrated checkout. Our responsibility includes supplying all facility interfaces, water and cryo-cooling, vacuum systems, and power wiring. Coordination of all beam testing or commissioning is done by AT-10, although specific experiments may be led by other groups.

Beam commissioning is the final step in the integrated quality-assurance process for verifying the performance of assembled beam hardware. We use extensive beam diagnostic equipment with integrated computer systems to measure beam parameters. Using these measurements, we compare actual performance with that predicted by beam-simulation codes. Validation of these codes is essential for improving confidence in future designs.

Group AT-10 was formed with its current mission in the fall of 1989; previously it had been AT-2, whose sole purpose since 1978 was to develop neutral particle beam (NPB) technology. Now the group's mission is changing again to reflect the broader responsibilities required by new projects. In the past, we concentrated on developing high-current, high-brightness negative-ion sources and injectors, such as those needed for the

NPB program. Although some negative-ion development will continue, we anticipate that most of our future work will require high-current, cw positive-ion or proton injectors. As a result, our latest thrusts are toward the integrated development of cw injector technology. AT-10 will continue to support GTA installation, operation, and commissioning. The experience gained and lessons learned in these endeavors will be applied to future AT-Division projects.

One of our senior staff members has been assisting with the design of and experiments on the Dual-axis Radiographic Hydrodynamic Test (DARHT) facility. In this instance, expertise developed on low-energy ion injectors is proving very useful for a high-current electron induction linac.

Background

Much of the group's work in FY 1992 was devoted to the commissioning and operation of the GTA hardware and characterization of the GTA beam. Cooling (at 20 K) for the cryogenic GTA was provided by a 750-W helium refrigerator. Installation and acceptance tests of a 40-kW cryo-cooling system were completed this year. Future experiments will use the increased capacity of this boiling-hydrogen cooling system.

We made a number of performance improvements to the GTA injector this year and proceeded with initial beam characterization of the intertank matching section (IMS) and the first GTA drift-tube linac (DTL) module. Meanwhile, we continued with the

assembly of a cw H^- ion source. This year marked our first serious entry into the design of high-current, proton ion injectors, a venture that may be essential for any of several emerging programs.

Achievements

Injector Systems

Operational reliability of the GTA injector was improved during FY 1992, and consistent high-current, good-emittance beams were obtained. A modification of the extractor and emitter electrode designs permitted faster and easier electrode changes. Source reliability was improved by several upgrades to the control system hardware, the installation of improved Allen-Bradley modules, and the installation of noise-suppression electronics. Changes in start-up procedures, operating points, and tuning have contributed to make recent source operation more consistent and have produced brighter beams.

Two Lambertson steering coils were designed, built, and installed inside the bores of the two low-energy, beam-transport (LEBT) solenoid magnets. These coils give much-needed beam steering into the radio-frequency quadrupole (RFQ). Figure 9.1 shows these steering coils during assembly. A reduction in LEBT length earlier in the year was instrumental in reducing emittance growth between the ion source and RFQ.

On the off-line discharge test stand (DTS), we installed a new 4X ion source that incorporates several design upgrades. The most significant upgrade is a new gas-pulser that uses a modified, low-cost, automotive fuel-injection valve to replace the previous piezoelectric valve. The new system reduced the total gas flow by nearly a factor of 3, without affecting arc operation. A reduction in hydrogen consumption may be important for reducing emittance growth in the LEBT. Configuration and cooling improvements were also made on this new source.

Fig. 9.1. Lambertson steering coils during assembly.

We have designed, built, and tested a new controllable arc-current pulser on the DTS. This pulser uses HEXFETs to control the source arc current; the HEXFETs replace the transistor on/off switch and ballast resistors. With this arc-current control, we have the possibility of programming the time dependence of the arc current during the arc macropulse.

Using internal Laboratory funding, we developed initial designs of a high-current, cw proton injector, suitable for projects such as the accelerator transmutation of waste (ATW) or the accelerator production of tritium (APT). A very similar D⁺ injector might be needed for a Fusion Materials Irradiation Facility (FMIF). To facilitate our design effort, we compiled available information from cw test stands both past and present. An extractor and solenoidal-focusing LEBT were designed for 75-keV, 140-mA hydrogen-ion beams. The integrated design was presented at internal

APT and Accelerator Based Conversion reviews.

We have also used internal funding to continue collaboration with the Chalk River Laboratory (CRL) and Grumman Corp. In FY 1993, we will ship \$5M of operating cw test-stand equipment from CRL to Los Alamos. Continued testing and development of this cw equipment at Los Alamos in subsequent years should strengthen our design capability for high-current proton accelerators.

In related work, we analyzed data recorded in previous years with a four-grid electrostatic analyzer to determine details of the space-charge neutralization of high-current H⁺ beams in low-energy transport. This diagnostic determines the internal beam potential by measuring the energy cutoff of the escaping charged particles. Using the measured energy distribution of the ejected positive ions, we measured the degree of neutralization or compensation as a function of argon and xenon

gas densities, thus determining when the beam became over neutralized. Proper space-charge neutralization is essential to eliminate problems with plasma instabilities in H⁺ beams. Figure 9.2 shows the observed compensation factor (*f*) as a function of gas density.

We developed a low cost, powerful, commercially based data acquisition and control system on the high-current test stand (HCTS). This stand-alone system is based on a Macintosh computer and expandable LABVIEW software, a graphical programming environment supported by National Instruments. The HCTS uses CAMAC and GPIB for all hardware interfacing, but future options include VXI/VME, Allen Bradley, and high-speed, waveform digitization. Provisions have been made to expand the present system to multiple computers as well as multiple platforms including SUN and IBM-PC-compatible systems. The software is based on the concept of multiple interactive pop-up windows, which give the operator detailed multilevel monitoring and control of the hardware.

We have been running design codes for ion extractors, including a custom design code and SNOW to simulate the plasma/beam interface and details of the ion trajectories. These codes were used to optimize the CRL cw test-stand injector performance. Subsequent tests confirmed a modest improvement in both beam emittance and divergence. In the future we will be forced to extend available design codes when designing the high-current, low-divergence cw beams needed on expected new programs.

The pulsed 8X source tests verified the scaling laws used to design the 8X source (as applied to the 4X source) and showed that there are no physics obstacles to building a cw 8X source. Our collaborator, Grumman Space Systems completed construction of the cw 8X ion source this year. We assembled and installed this source, along with a new high-pressure, heated,

Fig. 9.2. Compensation factor (*f*) as a function of gas density.

cooling water system on the modified HCTS. Testing of this cw H^- ion source should commence early in FY 1993.

Using the pulsed 8X source, we found that placing a conical collar at the emission aperture reduced the e^-/H^- ratio to 0.9/1 with no decrease in the H^- beam current. Without a collar, the typical e^-/H^- ratio is between 4/1 and 5/1. A barium cathode was tried in the 4X source in place of the cesium-coated, molybdenum cathode after we learned that a barium insert near the emitter of a cusped-field volume source increases the H^- current from that source by about a factor of 3. All indications are that the 4X source H^- output will be very low and the e^-/H^- ratio will be very high if a barium cathode is substituted for a cesium-coated, molybdenum cathode; therefore, we plan to use only cesium-coated, molybdenum cathodes in the 8X source.

GTA Beam Commissioning

A series of GTA beam runs were completed during FY 1992. In the spring, we fully characterized the output beam and operation of the IMS. This structure includes two rf bunching cavities and six permanent-magnet quadrupoles, two of which can be translated for beam steering and four of which have adjustable field strengths. The purpose of the IMS is to longitudinally and transversely match the RFQ output beam to the following DTL.

By maximizing RFQ transmission, we determined the optimal RFQ input match. The resulting Courant-Snyder parameters agreed with predictions.

During IMS testing, we measured both the transverse and longitudinal beam emittances for a variety of IMS quadrupole and buncher field strengths. We also measured the effects of beam steering in the IMS. The LINDA diagnostic remains the predominant method for characterizing the longitudinal-beam properties. In spite of identified difficulties, microstrip probes were used extensively for beam-centroid

position monitoring at several locations. Beam energy and phase were measured versus IMS buncher field, giving excellent agreement with design predictions. Figure 9.3 shows the observed buncher gap voltage versus cavity power and shows that the design gap voltage occurs at predicted power level. The beam steering and emittance measurements are being used to produce a steering and matching model of the IMS. These models are being used again in DTL experiments to verify the predicted performance of the DTL.

We conducted the first beam operation of DTL module 1 in September 1992 and produced a 3.2-MeV output. Future runs are planned for November 1992. We measured the transverse emittance of the DTL beam for a variety of input beam conditions and DTL operating set points.

High-Power Cavity Conditioning and Preparation

We have successfully conditioned three DTL modules. A successful conditioning consists of operating the modules at 20% over the required power levels for 2-ms rf pulse durations. The modules must also operate for long periods of time (tens of minutes) with little or no breakdown. As in the case of the RFQ, the DTL module 1 reconditions in less than 0.5 hour after extended exposure to the atmosphere and immediately each morning after an 8-hour nonoperation period.

Fig. 9.3. Energy difference between acceleration and deacceleration modes for cavity A.

Safety Systems Modification

The Radiation Protection Safety System was modified to include the first DTL module. This hardware-based system is modeled on the one used at Clinton P. Anderson Meson Physics Facility (LAMPF) and is designed to exclude personnel from the beam area whenever a radiation hazard might exist from beam operations. All GTA beam operations (with the exception of the 750-W cryo refrigerator) are conducted from the fully functional control room.

Cryogenic Cooling System

We presently cool the GTA beamline components to cryogenic temperatures with a Koch 750-W refrigerator. We operate a second refrigerator during multiple-magnet taut-wire (MMTW) measurements made on the IMS and DTL modules at cryogenic temperatures. The new 40-kW cryogenic cooling system (CCS) will be required for all GTA experiments that involve more than the RFQ, IMS, and first DTL module. This CCS obtains its prelimi-

nary cooling through a LN_2 to gaseous helium (GHe) heat exchanger and its primary refrigeration capability from a helium-to-liquid-hydrogen heat exchanger. The coolant pressure is 324 psig and the coolant flow rate is 484 g/s at 60% of the turbo-compressor speed.

We completed the final construction of the CCS and numerous reports and studies for the operational readiness requirements. On May 1, we received approval to take delivery of 15,000 gallons of liquid hydrogen to support the system acceptance tests which were successfully completed on May 8. Figure 9.4 shows the compressor and mechanical components of the CCS.

Beamline Alignment

During FY 1992, we internally aligned the drift tubes (DT) in four DTL modules to an accuracy of 0.001 in. at room temperature. The goal is to maintain 0.002 in. alignment when operational at 20 K and under vacuum. A second MMTW alignment system was built and installed in an off-line cryo-vacuum test vessel. Measure-

ments in this vessel confirmed that the required alignment was maintained under vacuum and cryogenic conditions for the first four DTL modules. We have adapted the MMTW system to measure not only the DT magnet centers, but also the magnet roll angle. We found that all DT magnet roll angles met the ± 0.5 degrees specification except one that had a one-degree roll angle.

We completed a number of floor layouts in preparation of moving the existing accelerator and setting the ten DTL modules. We also performed alignment for the Advanced Free Electron Laser.

While on an off-site assignment to AccSys Technology, one of our engineers provided linac design support for the Superconducting Super Collider Laboratory. He provided the analysis of the DTL temperature control system and the specification of the cooling and heating systems. He also designed and specified the rf power waveguide and window assembly.

Fig. 9.4. Compressor and mechanical components of the CCS.

Facility Support and Installation

AT-10 installed all GTA vacuum vessels and fulfilled all operational vacuum and cooling requirements. We continue to operate the helium refrigerators for GTA beamline experiments, high-power conditioning, and alignment verifications at cryogenic temperatures. All upgrades, additions, and maintenance to the GTA facility building as well as GTA electrical installations are our responsibility. Electrical installations include the rf mezzanine utility rack and distribution systems; CCS Instrumentation and Control, fire alarm, and protection systems; the telephone and paging system upgrades; experiment 2A beamline power-distribution system; control room and computer rooms electrical additions; power distribution to the mock-up DTL vacuum tank area; environmental, safety, and health upgrades and electrical power distribution system remodels; ground planes installations in the rf power area; and experiment 2D and 3 injector power trunk wiring installation.

DARHT Support

One of our senior staff members has been actively supporting the DARHT induction-linac electron accelerator project for the past 3 years. The first stage of the DARHT accelerator was completed this past year, and measurements of the 6-MeV, 3-kA beam are under way. Modifications of the injector pulsed-power system reduced voltage fluctuations during the pulse flat-top to less than 1% rms.

Insulator failures on the 4-MeV DARHT injector appeared to result from insulator surface charging. A device was built that measures and corrects if necessary the pulse-to-pulse charge buildup. In initial tests, this device discharged the insulator rings after each pulse; the tests for solving the insulator-breakdown problem were very encouraging.

AT-10's major responsibility has been to debug and use beam dynamics codes for the end-to-end electron-beam simulation. With this code, linear beam dynamics and nonlinear beam-breakup centroid motion can be tracked as a function of time during the beam macropulse. Some results indicate that space-charge effects are critical to the beam-breakup motion and can be mitigated only by careful design of the beam-transport system. AT-10 has also contributed to the data acquisition and analysis systems on the magnetic spectrometer, which will measure the time-dependent beam energy waveform to less than 0.5%.

Future Plans

For much of FY 1993, we will be preparing test-stand hardware for testing components and systems needed for high-current H^+ and H^- cw ion injectors. The initial test-stand configuration will permit us to test and compare several candidate ion sources. Later expansions of these stands will allow us to add and test transport components and, finally, to match beams into a RFQ.

Possible future projects such as the APT, the ATW, the FMIF, and possible major expansion of LAMPF and Manuel Lujan, Jr. Neutron Scattering Center will all require about 100 mA of protons or H^- ion currents. Individual components have been developed that might meet these basic needs, but our primary focus will be to integrate the technologies needed for building a practical ion injector.

We will continue to install GTA components and will move the GTA to a new location within the beam tunnel in preparation for experiments 2D and 3. In support of this move, we will supply all the utilities and will complete the floor installation. We will again lead the commissioning efforts on the first GTA DTL module and on the modified IMS and will work with the other GTA groups in analyzing the data. We plan to complete the alignment and the high-power conditioning of the remaining DTL modules.

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ABC	Accelerator Based Conversion
AFEL	advanced free-electron laser
APEX	APLE Prototype EXperiment
APLE	Average Power Laser Experiment
APS	Advanced Photon Source
APT	Accelerator Production of Tritium
ARES	Advanced Research Electromagnetic Simulator
AT-4	Acceleration Design and Engineering
AT-5	RF Technology
AT-7	Accelerator Theory & FEL Technology
AT-8	Accelerator Controls and Automation
ATW	Accelerator Transmutation of Waste
AXY	A = high-power accelerator, XY=represent the specific application
BCDTL	bridge-coupled drift tube linac
BEAR	Beam Experiment Aboard a Rocket
BESAC	Basic Energy Sciences Advisory Committee
BNL	Brookhaven National Laboratory
BOP	balance of plant
CAD	computer aided design
CAE	computer aided engineering
CCL	coupled-cavity linac
CCS	cryogenic cooling system
CEBAF	Continuous Beam Accelerator Facility
CERN	European Center for Nuclear Research
CLS-4	Photo Chemistry and Photo Physics
CLS-6	Advanced Laser and Systems Technology
CPU	central processing unit
CRADA	Cooperative Research and Development Agreement
CRL	Chalk River Laboratory
CTEN	Combined Thermal/Epithermal Neutron
cw	continuous wave
CWDD	continuous wave deuterium demonstrator
DARHT	Dual-axis Radiographic Hydrodynamic Test
dB	decibel
dc	direct current
DCM	downconverter module
DCN	Document Change Notice
DEWPOINT	Directed Energy Weapons Power Integration
DNA	Defense Nuclear Agency
DoD	Department of Defense
DOE	Department of Energy
DP	Defense Programs
dt	drift tube
DTL	drift tube linac
DTS	discharge test stand
ECAD	electronic computer aided design
EEV	English Electric Valve
EM	electromagnetic
EMP	electromagnetic pulse
EMQ	electromagnet quadrupoles
EMR	electromagnetic radiation
EPICS	Experimental Physics and Industrial Control System

ERAB	Energy Research Advisory Board
ES&H	Environment, safety, and health
ESNIT	Energy Selective Neutron Irradiation Test
FEL	free-electron laser
FMIF	Fusion Materials Irradiation Facility
FOX	far-field optics experiment
FWBPM	flying-wire beam-profile measurement
FWHM	full-width-at-half-maximum
G	gauss
GAC	Grumman Aerospace Corporation
GFI	ground fault interrupter
GL	gradient length
GPR	ground penetrating radar
GTA	Ground Test Accelerator
HAM	hybrid amplifier module
HCTS	high-current test stand
HEBT	high-energy beam transport
HIBAF	high-brightness accelerator FEL
HIPERGPR	high-performance ground penetrating radar
HPCTB	High-Power Cryogenic Test Bed
HPM	high-power microwave
HPP	high-pulse power
HPRF	high-power radio-frequency system
I&C	instrumentation and control
ICN	Integrated Computing Network
IMS	intermediate matching section
INEL	Idaho National Engineering Laboratory
IOC	input/output controller
ITF	Integrated Test Facility
JAERI	Japan Atomic Energy Research Institute
LAACG	Los Alamos Accelerator Code Group
LAMPF	Clinton P. Anderson Meson Physics Facility
LANSCE II	Manuel Lujan, Jr. Neutron Scattering Center II
LANSCE	Manuel Lujan, Jr. Neutron Scattering Center
LBL	Lawrence Berkeley Laboratory
LDRD	laboratory-directed research and development
LEB	low-energy booster
LEBT	low-energy beam transport
LEP	large electron positron collider
LINDA	laser induced neutralization diagnostics approach
LLNL	Lawrence Livermore National Laboratory
LLRF	low-level rf
LOG	large orbit gyrotron
LPCTB	Low-Power Cryogenic Test Bed
LVDT	linear variable differential transducer
MEBT	moderate energy beam transport
MMTW	multiple-magnet taut-wire
MP	Medium Energy Physics Division
MSDS	Material Safety Data Sheet

MST-7	Materials Science and Technology: Polymers and Coatings
NCLR	National Center for Laser Research
NCMS	National Center for Manufacturing Sciences
NERSC	National Energy Research Supercomputer Center
NLC	Next Linear Collider
NOP	normal operating procedures
NP	New Production
NPB	neutral particle beam
NPBSE	neutral particle beam space experiment
NSI	National Security Information
OFE	Office of Fusion Energy
ORNL	Oak Ridge National Laboratory
OTR	optical-transition radiation
P-15	Neutron Measurements Group
PAC	Particle Accelerator Conference
PEIS	Programmatic Environmental Impact Statement
PET	positron-emission tomography
PIC	particle-in-cell
PID	proportional, integral, and differential
PMQ	permanent-magnet quadrupole
POP	proof-of-principle
PSII	plasma source ion implantation
PSR	proton storage ring
QA	quality assurance
R&D	research and development
RDBMS	relational database management system
rf	radio frequency
RFQ	radio-frequency quadrupole
RKA	relativistic klystron amplifier
rms	root-mean-square
RPSS	Radiation Protection Safety System
RRR	residual resistance ratio at 4K
RSM3	rotating sample magnetic moment mapper
SAIC	Science Application International Corporation
SAIS	small angle ion source
SC	superconducting
SCR	silicon controlled rectifier
SDIO	Strategic Defense Initiative Organization
SLAC	Stanford Linear Accelerator Center
SNL	Sandia National Laboratories
SNSI	Secret National Security Information
SOP	standard operating procedures
SRD	Secret Restricted Data
SSC	Superconducting Super Collider
SSCL	Superconducting Super Collider Laboratory
SST	solid-state triodes
STATS	Separations Technology and Transmutation Systems
T	temperature
TTI	Technology Transfer Initiative

UPM	upconverter module
USASDC	United States Army Strategic Defense Command
VDM	vector detector module
VFPMQ	variable field permanent magnet quadrupole
VLE	vulnerability, lethality, and effects (VL&E)
VME	versa-module European
VXI	VME External Interface
VSWR	voltage standing wave ratio
WEC	Westinghouse Electric Corporation
WEMPE 4	wideband electromagnetic pulse environment
X-1	Inertial Fusion and Plasma Theory
XUV	extreme ultraviolet

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