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Accelerator Technology Division

Progress Report FY 1993

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Foreword

Foreword

We continued our mission for Accelerator Technology (AT) Division in fiscal year (FY) 1993 to pursue science and technology and to develop new accelerator concepts for research, defense, energy, industry and other areas of national interest. We had a successful year with a number of important accomplishments in our programs and initiatives. The following material highlights these developments. At the end of the fiscal year, the Laboratory aimed towards a different way of doing business resulting in a complete Laboratory restructuring. The restructuring resulted in AT Division and the accelerator part of Meson Physics (MP) Division forming a new Accelerator Operations and Technology (AOT) Division. This will be the last progress report from AT Division.

Fiscal year 1993 was the last year for major DoD (Department of Defense) programs in AT-Division. Although suspected, this fact was not realized until the end of the first FY 1994 quarter. Both the Neutral Particle Beam (NPB) and Free Electron Laser (FEL) programs received their last major funding in FY 1993. The NPB program received close-out funds in FY 1994 while the FEL program was closed in FY 1993 with only a few items being carried over to FY 1994.

In addition, events in our neighbor organization (MP Division) would have profound effects for the new AOT Division. Notice was given that FY 1993 would be the last year of nuclear physics support funding for operation of the 1-MW beam facility. This facility would be shut down and only D & D (decontamination and decommissioning) support would be provided in FY 1994. In reality, operation support would continue, and MP and AT Divisions would merge early in FY 1994. However, the shutdown announcement earlier in the year resulted in the loss of many senior and experienced MP personnel.

Primary thrusts in the NPB program were the Ground Test Accelerator (GTA) and the 8X cw ion source development. An aggressive GTA beam experimental program successfully measured beam properties in good agreement with calculated performance from a fully integrated accelerator system that included the first drift tube linac (DTL) module (beam energy 3.2 MeV), the intertank matching section (IMS), the radio-frequency quadrupole (RFQ) and the H⁻ injector. Fabrication and assembly of all ten of the DTL modules were completed, with the first five installed and aligned on the beamline by year end. All ten rf klystrons (with associated equipment) were assembled and partially tested.

In the 8X cw ion source development program, the high-temperature water cooling system was operated for the first time and attempts were made to run the plasma chamber in a cw mode.

Many of the more promising new program options for Los Alamos involve use of a high-current continuous-wave (cw) proton accelerator. The most challenging technical aspects of such an accelerator are at the "front end" where space charge forces, and beam initiation and matching challenges dominate. We are planning an Accelerator Performance Demonstration Facility (APDF) that will allow us to verify experimentally the suitability of our design for this very important low-energy region. Near-term work will involve the construction of an ion injector and preliminary design of the first 40-MeV portion, perhaps including a beam funnel.

At the beginning of FY 1993, management of the Chalk River Laboratory (CRL) in Canada announced intentions to abandon further development of cw ion accelerators. Because of our growing interest in cw accelerators, our previous collaboration with the CRL researchers, and our confidence in the high-quality work and equipment at CRL, we made plans to move their new injector and RFQ accelerator to Los Alamos. Internal institutional moneys funded a flurry of collaborations and the shipment of this equipment in April.

Defense Nuclear Agency (DNA) funding was used to reassemble the CRL hardware (now renamed the Chalk River Injector Test Stand (CRITS). Unpacking and reassembly of

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this equipment was underway by the end of the fiscal year. This hardware included an injector, a 1.25-MeV RFQ and two complete klystron-based rf power stands.

Several teams embarked on integrated design studies for a next-generation spallation neutron source—1 MW, with upgrade potential to 5 MW. Primary users would come from the materials science, biology, and physics communities. Our focus was the investigation of options for upgrading our operating 60-kW LAMPF/LANSCE from what is one of the world's most powerful pulsed-spallation neutron source.

Significant experiments were completed on the APEX FEL this past year that demonstrated successful photoinjector operation under very high-brightness conditions and with the production of UV light. Operation of this facility has shown that FELs can be made to meet stringent requirements. Work on the Advanced Free Electron Laser (AFEL) progressed very well, and we are expecting significant operation results in FY 1994. These results will demonstrate that FELs can be built compact, efficient, cost-effective, and user friendly.

A low level of collaboration continues on several international ventures. We are part of a multinational team investigating a superconducting structure for the International Fusion Materials Irradiation Test Facility (IFMIF). An interesting option on this is the JAERI proposal for a Energy Selective Neutron Irradiation Test (ESNIT) proposal.

One of the primary considerations for high-current accelerators is the minimization of beam loss to reduce component activation. Predominant beam loss is from particles in the beam halo. Extensive simulations and theoretical work is underway to identify the cause and growth of beam halos.

An interesting spinoff from our design work with permanent magnets are the "grippers" that can be mechanically turned on and off. The grippers are used for climbing the vertical sides of steel structures, including bridges, ships, and smokestacks.

In addition to these major programs, most of the groups in the Division were cultivating several small projects that utilize

relevant accelerator technology. Many of these smaller projects also supported specialized theoretical and experimental studies such as:

- understanding space-charge induced emittance growth
- tuning and stabilizing an eight-meter long RFQ
- evaluating super-conducting structures for LAMPF upgrades
- new sources of rf power
- optics codes refinements
- developing improved high-power microwave sources

Several of our employees received major awards, honors, and citations during FY 1993:

Rich Sheffield/John Fraser (retired)

1993 Prize for Achievement in Accelerator Physics and Technology from the Board of the United States Particle Accelerator School. This prize was presented at the Particle Accelerator Conference in Washington, DC

Dodge Warren

1993 International Free-Electron Laser Prize for outstanding contributions to FEL science during the past ten years. Prize award at FEL Conference in The Netherlands, August 1993

Tom Wangler

Selected Fellow of the American Physics Society, Division of Particles and Beams

Ray Stringfield and Team

Los Alamos National Laboratory's Distinguished Performance Team Award for experimentally demonstrating the principle behind the operation of the gyrotron amplifier

John Kinross-Wright

Los Alamos National Laboratory's Distinguished Performance Award for his participation in bringing about successful loading of the AFEL

ES&H continues to be a high priority for AT Division. A formal self-assessment program, including quarterly inspections was conducted by the division office. Many of our staff received ES&H training during FY1993. The Laboratory's Compliance and Assessment Group conducted a formal appraisal of AT Division's ES&H, quality assurance, security,

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and conduct of operations. Action plans were submitted for all findings, most of which were minor in nature.

Some training and waste management functions were consolidated into the division office to improve efficiency and quality. Discussions with MP Division and other TA-53 organizations were held regarding the implementation of facility management.

The Final Safety Analysis Report covering GTA 24 MeV operations was completed.

Over 245 publications were entered in the AT-Division publications database during FY 1993. 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 posters; conference assistance; proceedings preparation; and databases.

We approach FY 1994 with a mixture of concern and anticipation. Our traditional sources of support (major DoD programs) are clearly diminishing. There is hope for future growth in new areas such as the improvement program for LANSCE, the new 1 MW Spallation Source, the accelerator production of tritium (APT), accelerator transmutation of waste (ATW), and accelerator-based conversion (ABC) of weapons plutonium. The probabilities and rate of increase of these programs is hard to predict.

The following pages provide a summary of FY 1993 progress, first in our major programs, and then with somewhat more detail in the individual group summaries.

I would like to thank everyone in the Division for their contributions, insights, concerns, and for sharing their many talents. Your efforts, your striving for success, and working on teams are greatly appreciated. Thank you one and all.

S. O. Schriber

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This initiative, begun in 1993, was a feasibility study for a 1-MW next-generation spallation-neutron source by upgrading the existing accelerator system at the Clinton P. Anderson Meson Physics Facility (LAMPF) and adding a new accumulator ring, new target stations, and new experimental halls. The transition from the present LAMPF configuration to the next-generation spallation-neutron source is shown in Fig. 1.1.

The study was organized into three sections; accelerator/accumulator ring, target station/experimental facilities, and the required new buildings and improvements to infrastructure. Many groups at LANL participated in the study, with AT Division having the responsibility for the accelerator/accumulator ring and study management. A draft report of the study was prepared for an external peer review in January 1994.

This facility would serve the materials science, biology, and materials engineering community using neutron

scattering as a tool similar to x-rays or synchrotron light. An H^- beam is accelerated to 800 MeV, injected by stripping into an accumulator ring, and extracted as a 570-nsec high-intensity pulse at 60 pps and transported to a heavy metal target (such as tungsten) where copious neutrons are produced by spallation reactions. The system delivers 40 Hz to a high-intensity target and 20 Hz to a high-resolution target with a combined beam power of 1 MW. The present LAMPF facility has been a multiple use facility. This study is just one of several possible simultaneous uses of the accelerator and any plan must not preclude these other potential uses.

In the neutron scattering user community, the average experiment takes 4 hours. LAMPF has been used by the nuclear physics community in the past, where the length of a typical experiment is weeks or months. This difference in time to execute an experiment has significant implications on how the facility is designed and operated. The operating goal

is >90% availability for experiments during scheduled time and operation of the facility 9 months per year. This philosophy must be designed and built into the new facility. The following describes the configuration under study.

The accumulator ring injection requires the stripping of H^- into H^+ . Therefore, the preceding acceleration and beam transport systems must be designed for H^- beam. The existing LAMPF H^- source does not meet the current (40 mA) and emittance requirements. Various choices of H^- ion sources were studied and it was determined, that while many met some of the specifications, none of the existing candidates meet all the requirements. Little research and development have gone into meeting this particular need and several of the source candidates look very promising. After the source at 100 keV, the beam macropulse of 1200 msec would be chopped with a 1/3 off (235 nsec)-2/3 on (435 nsec) cycle to create the beam gap needed to generate the magnetic field to deflect the beam from the accumulator ring. Initial pulsing of the ion source followed by clean-up chopping at 100 keV is under consideration because of the space-charge neutralization in the low energy beam transport system. This system would replace the existing LAMPF Cockroft-Walton injector.

Fig. 1. 1. The 1-MW upgrade scenario. The figure shows the proposed upgrade of the LAMPF linac.

The beam is then accelerated up to 7 MeV by a new RFQ at 402.5 MHz. This RFQ is similar in design to that proposed for APT and is of conventional design, but longer and higher in energy to those previously built. This is followed by a new conventional room temperature 20-MeV drift tube linac at 402.5 MHz. At this energy, funneling can be added in the future should more current be required than one injector can supply. The acceleration stage from 20 to 100 MeV at 805 MHz has several candidates including: our base case—a conventional room temperature drift tube linac; a superconducting version; or new alternative structures under study by AT-1. Any of these would fit in the existing LAMPF tunnel replacing existing structures. The beam is then injected into the existing LAMPF coupled cavity linac (CCL) for acceleration to 800 MeV at 805 MHz. Tests on the CCL indicate it can carry the required current. The rf system requires upgrading of the local feed-forward system to ensure beam stability. The stored energy in the cavities is adequate to transmit the beam without excessive end to end droop in the cavity rf created by the chopping pattern. To meet the availability requirement, some infrastructure systems will need replacing and some redundancy provided.

Transport of the beam to the accumulator ring is partially accomplished through an existing beam line tunnel. The new accumulator ring would be buried under 35 feet of dirt for shielding with the support building situated directly above at ground level. The ring is a race track design with a period of 671 nsec for 792 MeV protons accumulating approximately 1788 pulses. Injection into the ring is by foil stripping with phase space painting of the beam by bump magnets to achieve optimum beam distribution and to keep foil traversals of the circulating beam to less than ten. The existing Proton Storage Ring (PSR) has shown large first turn losses traced to excited states of H^0 being stripped in the fringe field of the first bending magnet and subsequently not captured by the ring. AT-3 developed a unique solution of placing the foil in a magnetic field and using the energy separation of the hydrogen atomic states to capture cleanly some of the excited states and separate the remaining to an external beam dump.

The PSR has also exhibited a current dependent beam instability and tests were conducted this past year to provide information about the cause. It is believed to be an e-p instability, but the source of the electrons is still unclear. The minimization of electron sources is

one criterion for the new ring design. To this end, keeping protons out of the extraction gap is extremely important. A five-harmonic barrier-bucket rf system is under study, as are other methods of either producing the bucket or reducing the rf requirements. Extraction from the accumulator ring is by conventional pulse forming networks feeding a ferrite loaded kicker magnet.

An underground tunnel transports the beam from the output of the accumulator ring to the two target stations. The beam is injected vertically from below onto the targets to allow 360° of useful experimental floor surrounding each target station. These tunnels and the vertical bends are designed for transport of beams up to 2 GeV to allow for future upgrades to higher beam power and, if required, at higher energy.

Within AT Division, this study involved AT-1, AT-3, AT-4, AT-5, AT-7, AT-10, and AT-DO. A draft report of the study's progress was assembled and sent to 24 peer reviewers from all over the world. The formal review of this document is scheduled for January 1994. The comments of the reviewers and the remaining questions already recognized by us will be used to determine the technical areas for study in 1994.

single gap, 75-kV extractor that is similar to the fusion materials irradiation test (FMIT) injector design (Fig. 1.4). The accelerating-column insulators are well shielded from the beam and include electrostatic plasma rings to prevent charging. The 75 kV is divided across

Introduction

A proposal was submitted to the Defense Nuclear Agency (DNA) in FY 1992 to create the Accelerator Performance Demonstration Facility (APDF). APDF will develop a high-power continuous wave (CW) accelerator front end that is generic to high-power accelerator based applications (AXY) and that also has application to a future Los Alamos Meson Physics Facility (LAMPF) front-end replacement. The APDF accelerator is based on a proposed design (Fig. 1.2) for the Accelerator Production of Tritium (APT) Project. It consists of two identical 20-MeV, 350-MHz linacs, each generating a CW proton beam of 100 mA. Each of these 20-MeV linacs has an injector, a radio-frequency-quadrupole (RFQ) accelerator, a drift-tube linac (DTL), and a matching section between the RFQ and the DTL. The two beams are combined (funneled) together at 20 MeV and further accelerated in a 700-MHz bridge-coupled, drift-tube linac (BCDTL). The beam is then transported by the high-energy beam transport (HEBT) to the beam dump. The final output of the APDF accelerator is a 200-mA proton beam at 40 MeV.

Funding arrived the summer of 1993 allowing AT Division to initiate activities in three areas: APDF Injectors, APDF-RFQ Development, and APDF Integrated Design. These activities will be described in the following sections. AT Division is also funded to evaluate a LAMPF upgrade for high-power operation. Work in this task will be initiated in FY 1994.

APDF Injectors

Injectors are key to the successful operation of CW accelerators for the various accelerator (AXY) applications that need long-term reliability and stability. These requirements are the

primary drivers for the APDF-injector design.

The APDF injector (Fig. 1.3) begins with an electron-cyclotron-resonance (ECR) source. The ECR source was developed at the Chalk River Laboratory and used in Chalk River Injector Test System (CRITS) project (see CRITS, progress report this year). ECR has exceptionally high gas and discharge efficiency and has demonstrated long lifetime. A beam is extracted from the ECR source with a

two gaps with a water resistor. Vacuum pumping is done with turbomolecular pumps that afford stable, long-term pumping in the 10^{-5} torr range for optimum beam neutralization. The extracted beam is transported with a low-energy beam transport (LEBT) system that consists of a dual-solenoid lens. The dual-solenoid lens provides a range of tuning that allows optimum matching to the RFQ accelerator. Provision for automated fault recovery is incorporated

Fig. 1.2. A schematic diagram of the APDF Accelerator.

Fig. 1.3. A schematic of the APDF Injector.

the diagnostic and alignment requirement on the mechanical design. Figure 1.7 shows a schematic of the matching section.

RF work is being carried out in three areas. First, a top-level layout is being designed. There will be three basic systems.

- a 350-MHz, cw, 1.1-MW, klystron-based system for RFQs and DTLs,

- a 350/700-MHz, cw, 50-kW, klystrode-based system for bunchers and deflector cavity
- a 700-MHz, 6% duty, 1.2-MW, klystron-based system for BCDTLs.

Klystron efficiency at less than full output power is being studied. In the APDF accelerator, klystrons do not always operate at full output power because of varying power requirement. Using simulation, we are searching for the

optimum operation condition at various output-power levels. RF control with feedback and adaptive feedforward is being investigated for a cw system.

Other work includes investigation of coupled-cavity drift-tube linacs, beam operation, and facility issues.

Introduction

For a number of years Los Alamos National Laboratory has been developing photocathode sources of high-brightness electron beams for FEL applications. The APEX FEL was the first FEL to use a custom designed rf photoinjector as its electron source. The system consisted of a 1.3-GHz, 6-MeV photoinjector with a multi-alkali photocathode illuminated by a frequency doubled Nd:YLF drive-laser, followed by three separately powered accelerating structures that give a final electron energy of 46 MeV. Originally the FEL was designed to operate at a wavelengths near $3\ \mu\text{m}$, however the electron beam emittance and brightness were sufficient for harmonic lasing at much shorter wavelengths. We have demonstrated the tunability of the device from 0.37 to $11\ \mu\text{m}$. The report is a summary of the main contributions. (Further details can be found in the attached reference material.) In FY 1993 funding was provided by the US Army Strategic Defense Command and the US Department of Energy, Office of Defense Programs. Both programs were terminated in FY 1993. Beam was run at APEX for the last time on February 26, 1993.

The quality of the lasing in an FEL is critically dependent on the quality of the electron beam used to drive it. It has long been recognized that low-emittance, high-current electron beams from radio-frequency photoinjectors would revolutionize FELs both in terms of efficiency of operation and in the wavelengths that can be achieved with a given electron beam energy. The APEX device at Los Alamos was specifically designed to be the first test of a custom designed, integrated photoinjector-driven FEL. APEX was not the first FEL to lase using a photocathode electron source. The

Rocketdyne/Stanford (R/S) experiment achieved lasing near $3\ \mu\text{m}$ using a photocathode electron source in 1989. There were significant differences between the R/S and APEX photoinjectors: The APEX cathode produced 5 nC per bunch compared to 0.2 for the R/S experiment; the APEX cathode drive-laser delivered 10-ps pulses to the cathode compared to 100 ps for R/S. The net result was that APEX could produce a peak current of 350 A compared to R/S of 125 A, without the necessity for the momentum-filter and consequent beam loss of the R/S experiment. APEX also incorporated a solenoidal emittance compensation scheme that allowed operation of the photoinjector at low accelerating gradient.

The goals of the APEX experiments were:

1. Operate a photoinjector in a new high-charge ($> 1\ \text{nC}$), high-current ($> 100\ \text{A}$) low-emittance ($< 5\ \pi\text{-mm-mrad}$) regime.

2. Demonstrate the emittance compensation concept in accordance with simulations.
3. Study emittance growth mechanisms associated with transporting a high-current low-emittance beam and develop appropriate beam diagnostics.
4. Demonstrate and study stable high-gain lasing near $3\ \mu\text{m}$ and develop appropriate optical diagnostics
5. Design code benchmarking.
6. Transport electron beam in a 150-degree bend.
7. Push the lasing wavelength to as short a value as possible (UV lasing).

Items 1-6 were in support of the Average Power Laser Experiment (APLE)² at Boeing and were funded by the Army Strategic Defense Command, and item 7 was part of a Department of Energy funded program to demonstrate UV lithography of semiconductor substrates using FEL light.³

This report covers the highlights of the work and the details are contained in the papers included in the appendix.

Figure 1.9 shows the range of lasing wavelengths achieved at APEX since its initial operation in June of 1991. APEX has lased at wavelengths from the

Fig. 1.9. Operating wavelengths and approximate peak micropulse powers for the APEX FEL from June 1991 to February 1993. APEX operated with $\approx 10\ \text{ps}$ micropulses with a repetition rate of 21.7 MHz and micropulses that were typically 40-ns long at a 1-Hz repetition rate.

ultraviolet (UV) (0.37 μm) to the mid infrared (IR) (11 μm).

Electron Beam

The 46-MeV APEX accelerator used for these experiments has been extensively described.^{4,5,6} The accelerating tanks were coupled-cavity, standing-wave structures in the $\pi/2$ mode. The accelerator produced a 40-ms long macropulse-train of 8-15 ps full-width-at-half-maximum (FWHM) electron micropulses at a 21.7-MHz rate. The operating energy for the IR experiments was typically 40 MeV and was raised to 46 MeV for the UV experiments, the use of solenoidal emittance-compensation⁶ on the APEX photoinjector allows operation with a modest accelerating electric field of 25 MV/m at the cathode while still maintaining a low beam emittance. Without emittance compensation the APEX emittance would have been a factor of three higher according to Kim's theory.⁷ The low gradient allowed long macropulse capability. The ability to run long macropulses was important in the IR experiments involving sideband generation and suppression because of the long start-up time ($>10 \mu\text{s}$) for sidebands. The long macropulses were crucial to the successful UV lasing because of the long start-up time ($\sim 20 \text{ ms}$) of the FEL.

The emittance compensation achieved by the solenoidal focusing was partially compromised by the presence of rf quadrupole focusing in the photoinjector tank.⁶ This rf focusing partly disrupted the symmetry of the solenoidal focusing and reduced the emittance compensation such that there could be as much as a factor of two difference in the emittance between two orthogonal planes. The rf quadrupole resulted from an inadvertent choice for the orientation of the rf coupling slots between the accelerating and on-axis coupling cells. The problem was corrected in later versions of the photoinjector such as the AFEL at Los Alamos⁸ and the TUFEL injector built by Los Alamos for the University of Twente.⁹ As the beam traveled through the accelerator other emittance growth mechanisms became important. The most

significant of these, particularly at high-current ($>200 \text{ A}$), resulted from single-bunch transverse-wakefield effects. If an electron bunch travels through the linac structure off axis, dipole transverse wakefields can result in the tail of the bunch being kicked transversely with respect to the head. While the emittance of individual time-slices of the bunch does not grow, the time integrated emittance does grow. Different time slices of the bunch are matched differently into the wiggler resulting in diminished FEL performance. At high current ($>300 \text{ A}$) the emittance growth was more than a factor of two. This problem was solved by using a steering algorithm that was optimized to cancel the wakefield induced emittance growth.⁵

Figure 1.10 shows the rms normalized emittance of the electron beam plotted versus peak micropulse current. We have determined an empirical scaling relationship between rms normalized emittance (ϵ_n) and current for the APEX machine: $\epsilon_n = (1 + \epsilon/k) \text{ mm mrad}$, where I is the peak current (between 50 and 340 A), and the constant $k = 140 \text{ A}$. These measurements were taken with the accelerator operating with an output energy of 36 MeV. We can estimate the unnormalized or natural rms emittance for

the maximum energy of the accelerator of 46 MeV (see Fig. 1.10). Even though APEX was originally configured as an IR FEL, the emittance was sufficiently low to allow UV lasing with the use of an appropriate wiggler.

Infrared Lasing

The IR lasing had two main goals:

1. Demonstrate high-grain lasing using a high-current, low-emittance beam near 3- μm wavelength.
2. Study techniques of sideband suppression that would be applicable to high-average power FELs such as APLE.

The detailed specifications of the APEX FEL IR resonator and wigglers are given in Reference 5. The 6.9-m resonator is an asymmetric, near concentric design. The asymmetry results from placement of the optical waist at the wiggler center, which is 0.5-m upstream from the geometric center of the resonator. The resonator mirrors are made of CaF_2 substrates, that are coated with a multi-layer dielectric to give reflectivity in excess of 99% at 3.0 μm . A small fraction of light, which is transmitted through the optic, is transported to a diagnostic table located

Fig. 1.10. Emittance (normalized, rms, right-hand axis) versus peak current for the APEX accelerator. APEX used emittance compensation and the emittance predicted by theory for an uncompensated beam is also shown. The right-hand axis shows the unnormalized rms emittance for an energy of 46 MeV.

within 5 m of the out-coupler. Sensors on this table allow characterization of the small-signal gain, cavity loss, energy, spectral content, spatial intensity distribution, and temporal intensity evolution.

The wiggler used for the high gain IR experiments was an untapered all permanent-magnet Halbach design with four blocks per period. The period was 20.5 mm and the transverse gap was 4 mm. The rms vector potential was 0.85. The wiggler was 1-m long and had 49 periods.

Simulations assuming the above configuration and operating parameters have been performed using the FELEX¹⁰ code. This small-signal gain predicted by FELEX was approximately 200%. Our experimental measurements show gains in excess of 160%. We have found the small-signal gain measurements difficult to make. FELEX simulations show that the gain is large only for a small number of micropulses (approximately 10 micropulses or 0.5 μ s) at the start of the macropulse. Furthermore, rf transients at the start of the macropulse can make the initial lasing unstable.

When the FEL was lasing at wavelengths near 3 μ m, very strong sidebands were evident. In collaboration with Mission Research Corporation a series of experiments was performed on sideband suppression using the "Phase-Step Mirror" (PSM) technique.¹¹ This method of sideband suppression is based on the existence of a low-pass spatial frequency filter in the FEL resonator. When the optical beam is focused through the wiggler, the wiggler acts as a spatial filter. Increasing the spatial frequency content of the sideband light above the cutoff frequency of the spatial filter, while maintaining nearly diffraction-limited performance at the central (resonant) wavelength, increases the cavity losses at the sideband wavelengths. A PSM can be configured in numerous ways. We tested both single- and multiple-period PSMs.¹¹

We chose the step-height so as to shift the phase fronts of the resonant wavelength by an integral number of wavelengths and

to cause non integral phase shifts at the sideband wavelengths. Therefore the sideband light was severely aberrated and cannot be focused into the wiggler while light at the center wavelength was unaffected. The height of the raised areas was an integral number of half wavelengths at the resonant wavelength. Only one of the mirrors in the resonator was replaced by a PSM.

Experiments were performed with both multiple step and single step PSMs. The multiple step mirrors had fixed grooves machined onto a mirror surface (Cu). The single step mirror had no grooves; it was split in half, creating a single phase step. One segment was fixed and the other was attached to a piezo-electric actuator, allowing any desired step height to be obtained.

The experiments with the multiple-period PSM produced inconclusive results. The cavity losses were approximately 60% and the net gain per pass was 70%. The sidebands were suppressed; however, our simulations indicated that the laser, with such high cavity losses, would not support sidebands even without the PSM. A multi-step PSM with lower losses was not available.

The experiments with the adjustable single step PSM were more encouraging. Complete sideband suppression and transform limited, single line, wavelength tunable (2.8 and 3.1 μ m) performance were demonstrated for moderate small signal gain (up to 100%) and low losses (approx. 6%). The disadvantage of the single period PSM was that it could not provide sufficient contrast to assure complete sideband suppression when operated with extremely high small signal gain (see Reference 11 for more details).

Ultraviolet and Visible Lasing

The goal of a portion of our research was to develop an FEL that would lase at the shortest ultraviolet wavelength possible using a 46-MeV electron beam as a driver. When one considers that previous UV FELs have used electron beams with energies at 350 MeV (VEPP-3, 240 nm)¹²

to 800 MeV (Super-ACO, 350 nm)¹³ and that the shortest wavelength ever achieved by an FEL with comparable energy to ours is 1.4 nm (Mark III, 38 MeV)¹⁴, one concludes that our challenges were formidable.

The key issue for short wavelength lasing was the small emittance of the APEX machine and its weak scaling with peak current. It was this scaling that gives sufficient gain for UV lasing because the current could be set to a high level while still maintaining small emittance. The emittance only began to grow strongly for currents >200 A. We determined that the optimum choice of current for lasing near 375 nm was between 100 and 200 A. An electron beam peak current of approximately 130 A was chosen, with a micropulse width of 8-ps FWHM and 0.24% FWHM energy spread.

Our original plan for UV lasing involved the use of a pulsed microwiggler with a 5-mm period and $a_w = 0.7$.¹⁵ Our efforts at lasing with this wiggler proved unsuccessful.¹⁶ Fortunately our experience in working with the microwiggler and our success in transmitting the electron beam through a tube 1 mm in diameter and 300 mm in length, led us to consider building a permanent magnet wiggler, with a short period and a very small gap.

The permanent magnet wiggler¹⁷ that we used for lasing was a two-block-per-period Halbach design using SmCp magnets. The resulting wiggler period was 13.6 mm. The wiggler gap was chosen to be the minimum possible, subject to constraints imposed by the size of the optical and electron beams. The diameter of the matched electron beam was approximately 0.4 mm and the diameter of the optical beam at the ends of the wiggler was 0.7 mm. To allow some room for steering and matching the beam into the wiggler a gap of 1.5 mm was chosen. This gave an rms value of $a_w = 0.58$. The total number of wiggler periods was 73 with a total length of 1 m.

The arrangements of the wiggler magnets was such that the magnetization vectors

were parallel and anti-parallel to the wiggler axis, so as to enhance the gain on the 3rd harmonic. Gain on the 3rd harmonic is derived from two difference mechanisms. The fundamental component of a plane-polarized sinusoidal wiggler field generates gain on higher harmonics because the electron motion is not sinusoidal. In practice the wiggler field itself also has harmonic components. The 3rd harmonic component of the wiggler field generates 3rd harmonic gain by coupling with the 3rd harmonic component of the electron motion. These two gain mechanisms add or subtract depending on their relative phases.¹⁸ In our case these mechanisms add. If we had chosen an arrangement of blocks where the magnetization vectors were perpendicular to the wiggler axis then the gain mechanisms would subtract. We estimate (using Ref. 18) that our arrangement enhanced the 3rd harmonic gain by approximately 20% over that of the alternative choice.

The mirrors used were multi-layer dielectric (HfO_2 and SiO_2) on a quartz substrate. Light was extracted from the resonator by transmission through the mirror substrate. The mirrors had to satisfy some unusual requirements as outlined below.

The mirrors should have high reflectivity in the UV near 370 nm for 3rd harmonic lasing, and low reflectivity at three-times 370 nm, i.e., 1110 nm, so as to suppress lasing on the fundamental. However, we found it desirable to have high reflectivity near 1000 nm so that lasing on the fundamental would also be possible at a different electron beam energy from that required for 3rd harmonic lasing. We also required moderately high reflectance (~90%) at 527 nm, the wavelength of the photoinjector drive-laser. Injecting the drive-laser light into the FEL resonator and monitoring the multiple-pass ring, lasing was typically achieved over the latter 50% of the electron beam macropulse i.e., the laser start-up time was approximately 20 μs . The start-up time for lasing as predicted by simulations was 18 μs . Note that the optical down facilitates setting the initial

resonator length close to the spacing of sequential electron micropulses with an error of less than 100 μm . By lasing on the fundamental with an electron beam energy of 47 MeV the error in the cavity length could be reduced to less than 5 μm . Lowering the energy of the electrons to 45 MeV allowed lasing on the third harmonic while suppressing the fundamental. We used two multi-layer reflector stacks on each mirror: the upper one to reflect 360-380 nm light and the lower stack to reflect both 526.5 nm and 1- μm light.

Lasing was achieved on the fundamental at a wavelength near 990 nm using 47-MeV electrons and the cavity alignment and length were set. Then the electron energy was lowered to suppress the fundamental and lase on the 3rd harmonic. Lasing was achieved in the ultraviolet at wavelengths from 369 to 380 nm by varying the electron energy from 45.9 to 45.2 MeV. Care was taken to examine the optical spectra for the 2nd harmonic and fundamental during 3rd harmonic lasing to verify that no lasing was evident on these harmonics.

Detailed measurements were made at 380 nm and are summarized in the table.

Micropulse-pulse length was not measured directly but was inferred from simulations. Its length (6 ps) was less than the measured electron micropulse length (8 ps) because of the low gain to loss ratio.

The major difficulty in the operation of the ultraviolet FEL involved the alignment of the electron beam in the wiggler and resonator. Because the optical beam and the electron beam waist radii were about 200 μm at the center of the wiggler, the small-signal gain was very sensitive to alignment. We found that moving the electron beam off the resonator axis by as little as 100 μm was sufficient to drive the gain below threshold. Tilting one of the cavity mirrors by 5 μrad from optimum was sufficient to stop the lasing. The short cavity detuning length was also a problem. The full detuning length was approximately 17 μm . The cavity length was measured to change by approximately 0.02 $\mu\text{m/s}$ as a result of temperature changes in the FEL vault. A detailed measurement of the detuning curve was not possible because of drifts in the electron beam energy, optical cavity length and the mirror alignment. The lasing performance was very sensitive to the energy spread of the electron beam. An increase in energy spread by 0.1% was sufficient to drive the gain below threshold values. Visible lasing was also achieved on the 3rd harmonic near 510 nm with 39 MeV electrons.

Figure 1.11 shows a plot of lasing wavelength versus electron energy for a number of short wavelength FELs including APEX. The plot shows how APEX has moved from being a member of the low-energy IR family to wavelengths corresponding to the high-

Table 1. UV Lasing Performance

Electron beam energy (MeV)	45.2
Wavelength (nm)	380
Cavity losses per pass (%)	6.4 $\pm$ 0.5
Small signal gain, gross (%)	12.4 $\pm$ 1
Cavity detuning length (μm)	17
Macropulse length (μs)	20
Macropulse rep. rate (Hz)	1
Macropulse output power (W)	36 $\pm$ 5
Micropulse length (ps)	6 $\pm$ 1
Micropulse rep. rate (MHz)	21.7
Micropulse output power (kW)	270 $\pm$ 70
Micropulse intra-cavity power (MW)	25 $\pm$ 6
Extraction efficiency (%)	0.03 $\pm$ 0.01

Fig. 1.11 Electron beam energy versus operating wavelength for various short-wavelength FELs.

energy storage ring family, but at a significantly lower electron energy.

Applications

Two applications experiments were performed on the APEX FEL. The first involved IR photochemistry i.e., multiple photon dissociation of Freon gas, and took advantage of the sideband structure of the FEL light.¹⁹ Wavelength, tunability, sideband, and picosecond pulse structure are inherent characteristics of FELs that may be advantageous for photochemistry involving IR multiple photon dissociation. If tuned to an absorption resonance the FEL sideband structure will overlap the broad, excited-state spectral absorption and could lead to enhanced dissociation. The APEX FEL was operated with and without sidebands to test this hypothesis on CFC13 (Freon-11), one of the gases implicated in the depletion of the ozone in the Earth's stratosphere. The FEL wavelength was set to the C-Cl stretch absorption resonance at 11.8 μm, the oscillator was tuned first to minimize and then maximize spectral bandwidth (sidebands), and the light beam was focused through a pair of test cells (1.0 torr Freon + 1.7 torr air). Comparison of the final and initial absorbance spectra indicated that the CFC13 photo-dissociation yield was 1.2% for the cell

exposed to sideband spectra at 3% FWHM bandwidth and 9-ns micropulse separation. Negligible effect was seen without sidebands. The results of the single experiment were not large enough to be conclusive and further experiments are planned using the FELIX FEL at the FOM Institute in The Netherlands.

The second applications experiment involved using the UV FEL light for photolithographic imaging on photoresist-coated semiconductor wafers.^{3,20} These experiments were motivated by the potential application of FELs to projection lithography for commercial production of gigabit integrated circuits if the FEL wavelength can be extended to below 100 nm in the XUV. In our experiment we hoped to resolve several issues at longer wavelengths (375 nm) in the UV including:

1. photoresist response to trains of picosecond pulses with peak intensities $> 1 \text{ GWcm}^{-2}$,
2. benefits of adjustable temporal FEL coherence by lasing with sidebands,
3. control of spatial coherence to avoid fringe formation in the aerial images,
4. potential shot to shot beam jitter smearing of the lithographic images.

Our experimental results indicated that issues 1 and 4 should not limit

applicability of an FEL. Issues 2 and 3 could not be addressed because we were not able to produce sidebands.

Conclusion

The APEX experiments described here have demonstrated operation of a photoinjector electron source in the high-charge ($> 1 \text{ nC}$), high-current ($> 100 \text{ A}$), and low-emittance ($< 5 \pi \text{ mm-mrad}$) regime. We have demonstrated the emittance compensation concept which allows photoinjectors to operate at low accelerating gradient. We have shown that transverse wakefields can cause serious emittance growth in a low-emittance beam even in a short linac. We have studied a technique for the suppression of sidebands in an FEL using phase-step mirrors.

The performance of both the IR and UV lasing has been in close agreement with that predicted by computer simulations. We have validated the strategy of depending on improved emittance and harmonic lasing to achieve UV lasing with low-energy electrons.

The APEX FEL first lased at a wavelength of 3.6 μm on June 21, 1991. UV lasing was achieved on February 12, 1993. The electron beam was run for the last time on February 26, 1993.

Originally the APEX FEL had been designed to operate as a single accelerator master oscillator master amplifier (SAMOPA). The beamline for the SAMOPA was completed and the electron beam was transported throughout the entire beamline including the 150-degree bend. Because of funding shortages only the oscillator part of the SAMOPA was run as a laser and not the amplifier part and detailed studies of the 150-degree bend transport were not possible.

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Published Papers on APEX from 1990 to 1993.

The following is a list of published papers relating to APEX

Note: APEX was originally known as HIBAF (High-Brightness Accelerator FEL). The name was changed to APEX in March 1991.

Drive-Laser and Photocathode

1. "The Los Alamos FEL Photoinjector Drive-Laser," J.W. Early, et al., IEEE JQE, **27**, 2644 (1991).
2. "The Los Alamos FEL Photoinjector Drive-Laser," J.W. Early, et al., Nucl. Instr. and Meth., **A318**, 381 (1992)
3. "The Los Alamos High-Brightness Photoinjector," P.G. O'Shea, AIP Proc. **253**, 182 (1992)
4. "Photocathode Transfer and Storage Techniques Using Alkali Vapor Feed back Control," R.W. Springer, et al., Nucl. Instr. and Meth., **A318**, 396 (1992)
5. "First Dual-Sweep Streak Camera Measurements of a Photoinjector Drive-Laser," A.H. Lumpkin, et al., Nucl. Instr. and Meth., **A318**, 389 (1992)

Design Code Benchmarking

1. "Comparison of INEX with Accelerator and FEL Experiments," L.E. Thode et al., Proc. SPIE **1552**, 87 (1991).
2. "Design and Analysis of Experimental Performance of the Los Alamos HIBAF Facility using the INEX Computer Model," B.E. Carlsten, et al., IEEE JQE, **27**, 2580 (1991).
3. "INEX Simulations of Experimentally Measured Accelerator Performance at the Los Alamos HIBAF Facility," B.E. Carlsten, et al., Nucl. Instr. and Meth., **A304**, 587 (1991).

Electron beam and FEL Experiments

1. "Los Alamos High-Brightness Accelerator FEL (HIBAF) Facility," D.W. Feldman, et al., Proc. SPIE, **1227**, 2 (1990).
2. "Initial Results from the Los Alamos Photoinjector-Driven FEL," P.G. O'Shea, et al., Nucl. Instr. and Meth., **A318**, 52 (1992).
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10. "Performance of the Los Alamos HIBAF accelerator at 17 MeV," D.W. Feldman, et al., Nucl. Instr. and Meth., **A304**, 224 (1991).
11. "Operation of the APEX Photoinjector Accelerator at 40 MeV," D.W. Feldman, et al., Proc. Linear Accel. Conf., **603** (1992).
12. "Measuring Emittance of Nonthermalized Electron Beams from Photoinjectors," B.E. Carlsten, et al., Nucl. Instr. and Meth., **A331**, 791 (1993).
13. "Performance of the APEX 40-MeV Photoinjector-Driven Accelerator," P.G. O'Shea, et al. AIP Proc. **279**, 743 (1993).
14. "Performance of the APEX FEL at Los Alamos National Laboratory," P.G. O'Shea, et al., Nucl. Instr. and Meth., **A331**, 62 (1993).
15. "Experiments in Sideband Suppression on the Los Alamos Free-Electron Laser," C.J. White, et al., Proc. SPIE **1868**, 286 (1993).
16. "Lasing Attempts with a Microwiggler at the Los Alamos FEL," R.W. Warren, et al., Nucl. Instr. and Meth., **A331**, 48 (1993).
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Diagnostics

1. "Application of Streak Camera Techniques to FEL Experiments," A. H. Lumpkin, Proc. SPIE, **1552**, 42 (1991).
2. "Electron-Beam Diagnostic Development for the Los Alamos FEL Facility," M.D. Wilke, et al., Proc. Linear Accel. Conf., **817** (1992).
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1. "The Los Alamos POP Project: FEL Oscillator Experiments in the UV and Beyond," B.E. Newnam, et al., Nucl. Instr. and Meth., **A318**, 197 (1992).
2. "Infrared FEL Photochemistry: Multiple-Photon Dissociation of Freon Gas," B.E. Newnam, et al., Los Alamos National Laboratory Report LA-UR 93-3419 to be published.
3. "Photolithographic Imaging Experiments using a UV FEL," B.E. Newnam, et al., to be published.

Introduction

The design, fabrication, and installation of the GTA hardware continued at a brisk pace. The drift tube linac (DTL) module production continued very successfully. The assembly and testing of the rf power system on the mezzanine made great progress. The design, fabrication and installation of the controls and diagnostics hardware and software kept pace with the other efforts. Utilities installation progress was on schedule.

Two commissioning runs were interspersed in the building and installation effort. The first beam run in February and March was a continuation of the first DTL module performance evaluation that began last year (Experiment 2A). The second beam run in August and September was conducted in order to verify the performance of the intertank matching section (IMS) specially the steering model (Experiment C). In addition, the required performance of the microstrip probe as a beam positioning device had to be demonstrated.

Due to a funding decrease of the national Neutral Particle Beam (NPB) program, the GTA funding was reduced from \$39M in FY 1992 to \$20M in FY 1993. This required a significant reduction of personnel from an average of 150 people in FY 1992 to an average of 70 people in FY 1993. Naturally, this drastic reduction in manpower slowed down our progress considerably.

Commissioning of the Accelerator

Two experimental runs were undertaken during 1993. The first beam run in February and March essentially completed the performance evaluation of the first DTL module (Exp 2A extension).

The second run in August and September completed the IMS beam steering experiments of 1992 and served to measure the performance of the microstrip probes as beam position monitors (Exp 1C extension). (Fig. 1.12)

During Exp 2A extension, we measured beam centroid positions as a function of the DTL steering magnet position. Linear centroid motion was verified with the exception that inconsistencies between emittance scanner and microstrip beam position measurements persisted. Phase scans were performed for different powers in the intermediate matching sections (IMS) A and B. DTL phase scans were made for different cavity powers and input energies. Also the longitudinal emittance was measured as a function of the input energy. Output beam centroid

positions and angles were determined as a function of input centroid positions and angles. These data were used to determine the DTL transfer matrix. Centroid positions were also measured as a function of the IMS steering model. Other measurements included the beam centroid position as function of time during the beam pulse, drift tube gap voltage as function of DTL cavity power, rf phase stability and the performance of the rf predistorter. An automatic RFQ conditioner code was successfully tested.

Experiment 1C extension was conducted in August. It had three primary goals: explore the unexpected Exp 2A result that IMS focusing changes had very little effect on the DTL output beam; confirm the IMS steering model; and qualify the microstrip probes as the position measurement device for the entire GTA.

The data taken during this experiment are still under evaluation. Preliminary results indicate that a modified IMS steering model is acceptable and the microstrip probes can be used for believable beam position measurement throughout GTA.

Fig. 1.12. GTA control room (left to right: J. Jansen, K. Johnson, G. Bolme, B. Ingalls).

Injector

The injector effort had three goals: improve the reliable operation of the ion source; support the beam runs of GTA; and continue the characterization of source and low-energy beam transport (LEBT).

To improve the reliability a number of components have been replaced. The ion source was refurbished. It routinely produced a 2-msec beam.

A conical molybdenum insert was mounted on the inside of the source aperture in order to reduce the electron beam component. The parasitic electron beam causes extractor erosion and electrical breakdown. Measurements showed that the insert reduced the electron current by 16%. An ion current of 72 mA was obtained at the RFQ match point, the highest current so far.

Courant-Snyder parameters were determined at the RFQ entrance that resulted in the best RFQ transmission as a function of the LEBT solenoid currents. These measurements were used to validate the LEBT and the RFQ design codes.

The injector supported the 1993 beam runs very successfully during the extension of Exp 2A in February/March and during the extension of Exp 1C in August/September. (Fig. 1.13) With the exception of a few days of unsatisfactory performance the injector operated reliably.

DTL Module Fabrication and Testing

The GTA DTL consists of ten modules. The first five modules are configured in a focusing-defocusing cell sequence for 2- $\beta\lambda$ acceleration. The second five modules are configured in a focusing-focusing-defocusing-defocusing sequence for 1- $\beta\lambda$ acceleration. All modules undergo a sequence of preassembly, room temperature drift-tube alignment and tuning, final assembly, cryo temperature drift-tube alignment, and cryo-temperature, high-power conditioning. During the last year, module #6 and #10 were assembled, aligned, and tuned at

Fig. 1.13. Short LEBT and 4X ion source.

room and cryo temperature. Modules #7 and #8 were aligned, tuned, and partially assembled. Modules #6 and #10 were high-power conditioned. Fully tested modules #1 through #5 were installed in the vacuum vessel on the south side of the GTA tunnel. (Fig. 1.14)

A new taut wire alignment method had to be developed so that the drift tubes in the 1- $\beta\lambda$ modules could be accurately aligned. The taut wire signals from a focusing-focusing-defocusing-defocusing drift-tube magnet sequence cannot be as easily interpreted as the signals from a focusing-defocusing magnet sequence. The latter shows a signal reversal from magnet to magnet, whereas the former shows a reversal only between focusing and defocusing pairs. The modified alignment method worked satisfactorily.

Radio Frequency Power

The accomplishments of the rf power sector were made in the following areas: 1) completion of the design, installation and testing of the power conditioning system; 2) completion of the assembly and testing of the five 850-MHz modulators; 3) completion of the design, fabrication and testing of the low-level rf system and; 4) support of the two beam runs with rf power for the RFQ, IMS, and DTL.

The power conditioning system consisting of the 5-A high-voltage power supply, the large capacitor bank that delivers the 2-ms current pulse and crowbar circuits; cabling; safety devices; and a control rack was fully installed and successfully tested at full power into a dummy load.

Fig. 1.14. Five DTL modules installed.

The assembly of the five modulators was completed, the previously tested ten klystrons installed, and the modulators were tested for electrical breakdown. The first two modulators were successfully checked out with their standalone control racks. (Fig 1.15)

The design of the low-level rf system was completed and all printed circuit boards were manufactured by outside vendors. Acceptance testing of these boards has begun.

The cabling system and the wave guide runs were designed and cables and wave guides were installed.

The rf power system supported both experimental beam runs very reliably. During the 2A extension run, rf cavity field measurements were made that showed phase and amplitude well controlled within the 0.5°/0.5% requirement. The performance tests of the predistorer were satisfactory.

Fig. 1.15. 850-MHz klystron modulator control rack installed on-365 mezzanine (left to right: B. North, J. Bankrupt).

Beam Diagnostics

The diagnostics team concentrated on the redesign of the diagnostic plate that has been used to evaluate beam performance. The need for a redesign became obvious during Exp 2A because of a persistent discrepancy between scanner and microstrip probe beam position readings. The new design focused on improved rf shielding for the entire beam path on the diagnostics plate. Special attention was given to the need to mockup the actual geometry of the rf shielding in the vicinity of the microstrip probes located between DTL tanks. (Fig. 1.16)

Three experiments were conducted as part of the Exp. 1C extension beam run with the purpose of determining the performance of a microstrip probe in the real accelerator environment. They are: beam position determination with a one millimeter "pencil" beam; position determination with a three millimeter "diffuse" beam; and position determination with the mockup of the real geometry. The latter experiment was very

important because of the asymmetric image currents between DTL modules.

The experimental results were very satisfactory, especially the mockup experiment. The microstrip probes measured the correct beam position relative to their mechanical position on the beamline.

Controls

The controls team supported the ongoing design, fabrication and checkout of GTA subsystems. It also supported the two beam runs, Exp 2A extension and 1C extension.

The GTA software was consolidated so that it can be maintained independently from software used by other projects. This means that GTACS software was frozen on all existing Input-Output Controllers (IOCs). New IOCs will use the Experimental Physics and Industries' Control System (EPICs) version 3.9 which will be frozen for GTA.

A major operational improvement was achieved when the old L-net was

converted to an open network. However, this open network is still separated from the outside world. The GTA control system software had to be rebuilt for the new open/restricted network because addresses changed for most processors. All control system files were moved from the L-net and installed on the new open/restricted server. The L-net was decommissioned by disconnecting the servers and removing the classified disks.

Provisions were made so that archived experimental data be made available on the Macintosh network.

The GTA trunk cable database was consolidated into a single spreadsheet. This simplified cable design and layout for the entire GTA. The spreadsheet data were then incorporated into the master WIREFLEX project wiring data base. The installation of the trunk wiring was completed. Internal wiring harnesses for ten DTL modules were designed, built, tested, and installed. All GTA cabling that has been installed to date was terminated.

A prototype system for multiplexing timing signals into the control room was built and demonstrated. Under computer control, any of the GTA timing signals may be switched to any of the forty timing connectors in the control room.

Optics

The physics design for the 24-MeV bend and telescope was completed and presented to the US Army Space and Strategic Defense Command. The mechanical engineering design of the bend continued and a conceptual design review for the 3.1-m bend was held in January. One of the highlights of the review was a new magnet alignment technique that should simplify the alignment procedure.

Significant progress was made toward understanding and controlling the space-charge aberrations in the telescope. It was found that the strength of nonlinear correctors required to correct the space-charge induced aberration is less than the strength of the correctors for geometric aberrations.

Fig. 1.16 Diagnostics plate of Exp 1C (left to right: L. Dauelsberg, C. Vigil, G. Vaughn, and J. Mitchell).

The analysis of the rf power needs for the momentum compactor was completed.

In support of the national NPB program a space worthy design of a bend and telescope was developed for a particle beam concept enhancement and experiment definition (CEED) workshop at Grumman.

Experimental support

We followed through on an earlier decision to install the 24-MeV accelerator over the waveguide basement on the south side of the tunnel. This was consistent with the original plan to point the accelerator eastward and the telescope westward with enough distance available for the beam characterization system.

A very stable, high-strength floor was installed for the support of the vacuum vessels and the accelerator over the basement. DL vacuum vessels #2 and later #1 were installed on the floor. All peripheral vacuum equipment was installed and made operational. Finally,

after the installation of the ten waveguides, the entire system was evacuated and checked for vacuum leaks. The first five DTL modules were installed in tank #1.

The RFQ/IMS vacuum vessel was then moved into position with the RFQ and IMS still inside. After rough alignment, the vessel was rolled back to prepare the floor anchors. The entire waveguide system was installed. It reaches from the klystron modulators on the mezzanine down the west shaft through the tunnel and waveguide basement up to the DTL modules.

Electrical power, water, air, and N₂ lines were installed for the south wall location. Cable trays and conduits, I&C, and power cables were also installed to serve the accelerator in its new location.

Experimental support was provided for Exp 2A extension and Exp 1C extension. In addition, we supported low-power tuning and alignment and high-power rf conditioning in our two test facilities.

Summary

FY 1993 was a very busy year for the GTA team. We had two beam runs of about one month each. These runs were very important because they permitted us to complete the performance evaluation of the IMS and the first DTL module which had been begun in FY 1992.

During the times when we did not run the beam we continued the installation and integration of the hardware and the data analysis.

Because of the abrupt change in the direction of the national directed energy weapons program GTA 24 cannot be completed. The anticipated funding of about \$6M for FY 1994 will be used to mothball the facility. This gives AOT division and the U.S. Army an opportunity to find a new sponsor to fund the completion of GTA for a new purpose.

Work with the DOE Office of Fusion Energy and the international community continued, with further steps toward the design of an intense neutron source for fusion materials development based on the D-Li (deuteron bombarding a lithium target) accelerator-driven system. The US ad-hoc committee chaired by M. Saltmarsh of Oak Ridge National Laboratory (ORNL) helped organize and attended a July workshop in Moscow. Agreement was obtained from the Russian, Japanese, European and US delegates to proceed with an international proposal, to be made to the IEA and ITER in 1994, for an International Conceptual Design Activity (CDA) on an International Fusion Materials Irradiation Test Facility (IFMIF). The possibility that superconducting accelerator technology, after a suitable R&D program, would provide a better facility in terms of both technical and economic factors, was presented and accepted as a design strategy. The accelerator required for this facility would provide 35-40 MeV deuterons at cw beam currents of 250-500 mA. A few persons from each partner would be involved in the CDA. In preparation for this effort, work was done with the industrial team lead by Grumman Aerospace & Electronics that was engaged this year to help with pre-conceptual design activities.

Work also continued¹ with the Japan Atomic Energy Research Institute (JAERI) Energy Selective Neutron Irradiation Test (ESNIT) facility proposal effort. This facility would use a 50-100 mA deuteron linac for materials research. The optimization process for the radio-frequency-quadrupole (RFQ) accelerator was extended to more clearly show the parameter space complexity of this type of linac and indicate how the simplified analytical estimating procedures used for preliminary design can be improved. A

frequency-doubling 175/350 MHz baseline design was developed and used for preliminary investigations of the energy-selective feature. Transport of a coasting beam down to 10 MeV was shown to be feasible, but complications arise with the typical room-temperature tank layout in providing the desired $\pm 1\%$ mean-energy dispersion to spread the energy deposition in the target. Work on the beam tailoring system to provide a two-dimensional uniform beam distribution at the target also continued. The added complications of the energy-dispersion system, bends to reach the target areas and to avoid neutron backstreaming, and space-charge require substantial effort. Continuing work will explore the use of superconducting accelerator technology to replace the drift-tube linac; among other benefits, the shorter tanks are expected to enhance the energy-selective features. Detailed considerations for the design and construction of electromagnetic quadrupoles for drift-tubes were also developed.

JAERI OMEGA Project

A small effort continued on JAERI-funded conceptual studies related to the OMEGA 1600 MeV, 10^{-3} -mA cw proton linac intended for the evaluation of accelerator-driven transmutation of radioactive wastes. For this year's activity the OMEGA team requested a point reference design outlining an overall approach believed feasible for the project. Based on the extensive work by AT Division on the AXY programs, the outline of such an approach was provided.²

Two subtasks were contracted that relate to the IFMIF/ESNIT, OMEGA and AXY work. The first was an assessment of the rf-driven multicusp ion source for these applications, by Lawrence Berkeley

Laboratory (LBL).³ The second, by the Moscow Radiotechnical Institute, provided an extensive discussion of their design techniques for high-intensity ion accelerators⁴, application of these techniques⁵ to an analysis of two LANL high-power accelerator designs (cw 100-250 mA deuteron linac to 40 MeV and proton linac to 1.6 GeV), and development⁶ of the beam halo phenomenology that is outlined elsewhere in this Progress Report.

The Physics of Beam Halos

A diffuse outer halo of beam particles is known to form around the central core of intense, non-relativistic ion beams in operating accelerators such as LAMPF. The cause and evolution of these halos has been the subject of investigation and discussion for many years, but remained elusive. Intensive numerical studies^{7,8} this year have elucidated much of the physics that leads to the main halo effects that plague high-intensity machine tuning. Many typical small errors in a machine cause the beam to be somewhat mismatched in the channel, and density modulations occur in the particle distribution. A first primary effect was found to be that single particle interactions with a beam core that is non-stationary in time or position can transfer large amounts of energy to the single particle. This is shown schematically in Figure 1.17. Particles can gain or lose energy during a single interaction. An analogy is the trajectory boost achieved by sending space satellites near a large body.

The single particles may have resonant interactions as their tune resonates with the core oscillation. These resonances are a second primary effect, and can move particles from near the origin out to several rms standard deviations. This phenomenon (that central particles can end up in the halo) had been observed before in simulations but never explained. A very important corollary is that the single particle tune is changed during the resonant interaction, causing it to fall out of resonance, and thus the halo production is self-limiting. Figure 1.18 shows how

Fig. 1.17. Schematic of collective core/single-particle halo-producing mechanism.

halo particles that pass through the core when the core density is rising will be moved farther out; their tune changes and they fall out of phase on the resonance and move back in, and then out again.

This is a crucial point of great importance in machine design, because providing a larger beam bore to avoid particle scraping losses is expensive. Until now, we had imagined that halo production was some kind of continuous and unbounded diffusion process. Knowledge of the bounded nature of the process outlined is of great value in understanding the bulk

of observed halos. The process can also be described in terms of chaos/stochasticity theory. Here it becomes clear that in the 6-D plus time dimensionality of a real accelerator, there will undoubtedly also be leakage through the stochastic web to even larger radii. A number of workers around the world are now rapidly expanding these investigations.

The particle interactions with the core can be visualized in many ways – some are rather beautiful, such as in Fig. 1.19.

References

Fig. 1.19. rr' versus r for a halo particle. The shade of each dot represents the central density; black is most dense. The size of the dot represents r' ; a smaller dot indicates a smaller r' velocity.

Fig. 1.18. Resonance and self-limiting behavior of halo particles (studies of a warm mismatched beam in a radial focusing channel).

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to demonstrate this feasibility of a resonantly-coupled segmented RFQ structure, the CWDD cold model was extended to eight meters in length and modified to operate as four segments. The design of this was completed during FY 1993 and fabrication and testing is scheduled for FY 1994.

Superconducting RFQ Linac

Design of a prototype niobium superconducting RFQ linac was begun in FY 1992. During FY 1993, fabrication tests were carried out and the detail design of the RFQ and its cryostat insert were completed. This unit is shown in Fig. 2.3. Fabrication and testing are planned for FY 1994.

Fig. 2.3. Niobium superconducting RFQ linac engineering model.

Beam Dynamics Section

Understanding Space-Charge Induced Emittance Growth

An analytic formula has been established to express the dependence of space-charge induced emittance growth on various beam parameters. The beam model

assumes a parabolic density distribution with elliptical cross section, which produces the nonlinear space-charge forces that give rise to the emittance growth. We consider a charged particle beam with elliptical cross section that propagates in a drift space in which there are no external fields. The space-charge force will cause a change in the momentum components, which is equal to the product of the force times the time over which the force acts. The force depends on the spatial distribution of the particles, and the spatial coordinates of the particle on which the force acts. In general, these changes in the momentum components will change the phase-space distribution of the particles. In the model the spatial distribution is assumed to remain unchanged as the beam propagates. In a first approximation, a transport channel can be represented by a sequence of such short drift spaces separated by thin-lens focusing elements. The model shows a result that had been seen in many numerical simulations, but had not been understood namely that the emittance growth in a given plane increases with increasing beam size. That the emittance growth increases as the size increases may seem surprising for an effect that arises from space-charge force, which increases as the beam size becomes smaller, rather than larger. The explanation is that the relative field components, and therefore the relative divergence kicks, are insensitive to the semiaxis sizes. However, emittance is an area in phase space, and is essentially a product of the divergence spread times the spatial extent of the beam in that plane. Therefore, if the divergence kicks are comparable in the two planes, the emittance growth is larger in the plane that has the larger semiaxis length.

Beam-Halo Model

A model was used to understand the results of numerical simulations of halo formation in mismatched beams. In this model the envelope equation for a mismatched uniform core and the equation of motion of a single particle interacting with that core and focused in the linear channel were numerically

integrated. The model was interpreted as a lowest order description of the interaction of individual particles for the initial Gaussian beam like that studied in the simulation. The central part of the Gaussian distribution is thought of as the core. The model revealed the presence of the same types of trajectories observed in numerical simulation. Certain trajectories had properties that qualitatively explained several features of the core and the halo. These trajectories had characteristics of chaotic behavior in that their coordinates were very sensitive to the initial conditions. They were identified with the particles that were most strongly affected by a parametric resonance between the particle motion and the mismatched core oscillations. Such particles spent time in both the core and the halo, and spent little time in between. Their erratic motion in the core may lead to the rapid homogenization of the core that is observed in the simulations. An example of such a trajectory is shown in Fig. 2.4. If the beam was collimated to remove the halo, one would be removing the betatron trajectories and only those resonant particles that were located in the halo at that time. The halo could regrow as resonant particles that happened to be in the core moved back into the halo region. All this sounds discouraging for being able to remove halo by using collimators. However, it appears that the resonant particles have maximum trajectories that depend on the initial mismatch, and are nearly independent of the initial coordinates. Thus, if the mismatch is known, the collimators are effective in defining a clean beam at some larger emittance than that defined by the physical size of the collimator. In other words the post collimated beam would regrow a halo with limited maximum amplitude.

Superconducting Section

The primary emphasis of the superconducting cavity effort was related to the 4-cell, 805-MHz cavity. Programmatic changes necessitated changing the original 7-cell cavity order to 4 cells and to be compatible with intense proton beam applications foreseen

Fig. 2.4. Phase-space plot over 20 core oscillation periods of a trajectory that is strongly affected by a resonance between the particle motion and the mismatched core oscillation.

for potential LAMPF upgrades. The downsizing to 4 cells also allowed for testing the 4-cell cavity in existing facilities in the superconducting laboratory.

Work during this year included designing the proper insert and equipment to test the cavity in the lab. In addition, effort was put into modifying the high-power klystron in the structures lab to produce up to 100 kW at 805 MHz to test high-peak power processing on the cavity. This entailed installing two LAMPF bucket rotator klystrons, designing and ordering the necessary coaxial line, and testing the components.

To do high-peak power processing, a fully-brazed 3-1/8 coax window has been designed and built to withstand the rigors of cryogenic cycling. The window has been tuned for low reflection ($VSWR < 1.02$), and initial tests up to 800 W show the window to have a low rf loss.

Testing on single cell 805-MHz cavities was used to evaluate high-pressure water rinsing for cleaning cavities. In general, cavity performance improved in two out of three tests when cleaned with 700-psi ultrapure water. The results of this work have been applied to developing advanced cleaning and processing procedures that will be used on the 4-cell cavity.

The balance of effort went into fabricating parts for the 4-cell test, including insert lid and components, building a clean-room cavity cart, designing and building a Joule-Thompson expansion valve for flash-cooling liquid helium, and modifying the existing high-pressure water sprayer to accommodate the 4-cell cavity.

Technical Notes

The following AT-1 Technical Notes were written during the report period:

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AT-3

Magnetic Optics and Beam Diagnostics

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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 optics systems. To fulfill its mission, the group maintains experimental and construction facilities that include a diagnostics laboratory, which fabricates beam-diagnostic electronics; a magnet-measurement laboratory, which performs precision measurements on a wide variety of electromagnets and permanent magnets; a mechanical design, fabrication, and assembly section; and a laser development facility for our laser induced neutralization diagnostics approach (LINDA) measurement system. The group is also responsible for managing a staff machine shop and maintains full vacuum leak checking capabilities.

AT-3 carries out projects in cooperation with industry and other divisions in the Laboratory. One of our major strengths is our ability to produce beam transport, diagnostics, and magnet systems for the full project-life-cycle of system definition, design, construction, commissioning, operation, and maintenance. We maintain expertise in high-order optics theory and codes with an emphasis on practical design, construction, and implementation. We are concerned with innovative and conventional diagnostics for controlling the high-intensity beams associated with modern linacs. We have a world class facility for magnet design, and we have developed a magnet lab with equipment suitable for measuring a large variety of magnets—from small cryogenic devices to large-bore pulsed magnets.

Our most important asset is our people and we are careful to keep them technically knowledgeable and at the forefront in their areas of expertise. Our people are regular attendees at the Particle Accelerator Schools both in the US and at the CERN schools, and they are active participants in the LINAC and Particle Accelerator Conferences as well as more

specialized conferences in optics, magnets, and diagnostics.

Overview of Activities

Our main efforts during FY93 have been in support of the Ground Test Accelerator (GTA), Los Alamos Meson Physics Facility (LAMPF) operations, the Super-Conducting Super Collider (SSC), and the LANSCE II study:

- The Ground Test Accelerator (GTA) program is an experiment to demonstrate most of the technology required for a space-based neutral-particle beam for defense purposes. Our most active roles have been in identifying, developing, and participating in experiments, providing both permanent and temporary-specialized diagnostics for the commissioning of the linac. Additionally, we have participated in the design and construction of magnets for GTA and have been entirely responsible for measuring the many magnets used by the project.
- We provided beamline tuning and experimental facility support for the WNR (Weapons Neutron Research) facility at LAMPF during the 1993 summer running period.
- Several AT-3 group members were included with the 20 AT-Division personnel that participated in an inter-laboratory arrangement to provide physics and engineering support for the SSC. An AT-3 group member was the coordinator for this endeavor.
- LANSCE II is the study for a 1-MW next-generation spallation-neutron source. Our group has been the major contributor to the accumulator-ring design.
- Accelerator Driven Transmutation Technologies (ADTT) may provide the solutions for the non-reactor production of tritium required for national defense—Accelerator Production of Tritium, (APT), the efficient burning of industrial nuclear waste and eliminating the necessity for long term storage—Accelerator Transmutation of Waste (ATW), and for

the disposal of the world's excess of plutonium—Accelerator Based Conversion (ABC). Our group is heavily involved in providing conceptual beam transport channel designs for these proposed programs.

- Further efforts were expended in magnet work for the US Navy and participating in proposal studies for several potential future Division projects.

Achievements

Optics Section

The optics section is involved in the design and analysis of transport lines, linacs, telescopes, bends, matching sections, storage rings, and nonlinear beam-expander beam-redistribution systems using beam dynamics computer codes such as TRACE-3D, MARYLIE, TRANSPORT, PARMILA, TLIE, and DIMAD. We are major participants in the development of Marylie, TRACE-3D, TLIE, & Bedlam. TRACE-3D is a workhorse design tool maintained in this group. The University of Maryland/Los Alamos collaboration has led to our use of the Lie Algebraic beam optics design and analysis codes Marylie and TLIE. Marylie is our workhorse code for 3rd order design, while TLIE is a new code capable of analysis up to 16th order. Large parts of the codes were written here to meet programmatic needs. BEDLAM is a new moments code being developed for space charge research. The Strategic-Defense-Initiative Neutral-Particle-Beam (NPB) projects (GTA, NPBSE) have provided experience in the design of achromats, momentum compactors, and energy and phase correction techniques. The experience gained from designing many proposed output telescopes for the NPB projects has helped the optics section develop a special expertise in the applications of high-order optics, in particular the techniques of scanning the manifold of first order designs, and the aberration hyperspace for optimal magnetic contouring (cf. cancelling third order aberrations while simultaneously minimizing fifth order aberrations).

The Optics Section was a major contributor to the GTA program which is an experiment to demonstrate most of the technology required for a space-based neutral-particle-beam device for defense purposes. A low-divergence beam is required at the exit of the final GTA telescope optics.

Beam energy spread and energy jitter coupled with chromatic aberrations in the telescope optics increase the beam divergence. Control of the beam energy spread and jitter is required. We estimated the beam energy and phase jitter expected for the 24-MeV GTA experiment using several models. We found that the energy jitter is small enough to be correctable by a two-frequency energy-compaction system. We found that rf nonlinearity effects are not large enough to require additional energy correction cavities or special control of the rf tanks. (Provided the rf phase on the energy-compactor cavity is correct, the compactor will correct for both energy spread and beam centroid energy jitter.) We estimated that the maximum beam phase jitter will be about 3 degrees. The energy-compaction cavity rf phase will have to follow the beam phase to within about 0.5 degrees to keep the final energy spread (after energy compaction) within the amount required by the final optics. We investigated the possibility of using the final rf tank at 24 MeV to correct for beam energy or phase jitter. We found that this approach could be useful to correct for energy jitter should its value turn out to be larger than the 50 KeV value that can be handled by the energy-compaction system. Accuracy of correction is not important. It is only important to reduce the energy jitter to below the 50 KeV value. We determined bend apertures for the 3.1 m GTA-24 bend, estimated misalignment and multipole effects. This work required writing specialized simulation codes. We also studied a straightened 2-D beamline for GTA-24. We participated in GTA commissioning for the first DTL tank and did some analysis related to measurements of transverse and longitudinal motion in tank.¹

One area of our involvement was the effect of geometric aberrations induced on a beam by the magnetic optical elements. The most interesting result about the geometric aberration problem is the concept of "Dynamic Aperture" of an objective. The nonlinear magnetic forces on a particle, that produce geometric aberrations, are proportional to the displacement of the particle from the magnetic axis. If you plot, the contour of particle displacements, from the magnet center, through the magnets that produce a one-microradian aberration for various magnetic channel designs, you can use the area enclosed as a figure of merit. In some sense the correctors are designed to increase this area. Also, since the area is almost never circular, using a slightly elliptical beam can maximize the beam on target.

We developed the moment method of characterizing a charged particle beam bunch distribution for the efficient and accurate calculation of space-charge forces. We presented the status of this BEDLAM optics code at the 1993 Computational Accelerator Physics Conference. What is new in this paper is an analysis of higher order space-charge effects that can be seen in higher-order codes like BEDLAM but not in linear codes like TRACE3D. An interesting effect is the existence of stable motion in bright nonuniform beams in which the space-charge forces near the beam center can be larger than the focusing forces.

The Optics Section produced the beam transport and targeting system for the ADIT project. ADIT may provide the solutions for the non-reactor production of tritium required for national defense—APT; the efficient burning of industrial nuclear waste and eliminating the necessity for long term storage—ATW; and for the disposal of the worlds excess of plutonium—ABC. We completed work on a high-energy beam transport and beam-redistribution system for high-energy, high-intensity beams such as are associated with the APT and ATW projects, where the objective is to produce a beam of approximately uniform intensity for impingement on a target.

The line is conservative, has a modular layout to accommodate many applications, and produces sufficiently uniform beams of large area. The line can deliver beam to several targets and to a beam dump during accelerator tune up. The line physically separates target areas from the accelerator and from each other, allows characterization of the beam, and deals with the low-momentum component of the beam. The 200-mA, 1-GeV APT beam is 0.5 m by 1.0 m on target, and 1.5 m by 3.0 m at the beam stop. Tuning to change the size of the irradiation area at the target is possible. Beam-jitter control and the proper beam focus into the nonlinear expander are important. In the later phase of the design, special attention was paid to a system with beam-envelope properties that allow shielding and a layout that facilitates dealing with the back streaming neutrons.

We did PARMILA simulations of the APT high-energy beam transport. Since we used particles from a simulation in the final section of the accelerator which we transported to the final target position, this work represents the final piece of an end-to-end simulation of the whole system. Figure 3.1 shows the scatter plot for the 10,000 particles on the target. The statistics of this distribution are not quite good enough to conclude that we have no hot spots above 20% over mean intensity.

Fig. 3.1. Beam spot (x-y distribution) at ATP target. Units are cm. The goal is to produce a uniform rectangular beam.

During FY 1993, the line was presented in two meetings, the "Workshop on High-Power Accelerators for ATW/ABC Applications" November 16-20, 1992, and the "APT Design Review" March 1-3, 1993. By that time, diagnostics and loss-of-defocus issues had also been addressed.

We participated in the operation of LAMPF during the summer of 1993. Procedures were developed to obtain beams that met users' requirements. Documentation that will be needed by future beamline physicists and users was also accomplished.

Beam Diagnostics Section

During FY 1993, the AT-3 beam diagnostics team participated in many of the AT division projects. This participation included all facets of the multi-discipline area of beam diagnostics. For example, we conceptually designed and planned new accelerator beam diagnostic measurements for newly designed accelerator facilities. We also completed detail designs of beamline mechanical and processing electronics components, fabricated and installed complete measurement systems, and helped commission and maintain beam instrumentation and carry out the experimental programs for existing charged particle beam facilities. During this year, various members of our team contributed to the 1993 Linac and Pulsed Power Conferences and the 1993 Beam Instrumentation Workshop and attended several technical short courses and UNM based college courses.

The primary project for FY 1993 was the participation in the latter stages of the GTA experimental program. During this period, we improved the state-of-the-art technology for noninterceptive beam diagnostics instrumentation. For example, we adapted the mathematical model for image-current-based beam position measurements and mounted an experiment that verified this model. The existing theory did not include effects to the sensitivity of image current based beamline devices to low velocity beams. The change to the previous model for

Fig. 3.2. The above figure shows the effects of low-beam velocity to two different radii image-current-based probes used for beam position measurements. The abscissa is $\beta\lambda$ (the distance the bunch travels in an rf period) and the ordinate is the probe's increase in sensitivity above that typical for beams traveling at velocities very near the speed of light.

beam position measurements is summarized in Fig. 3.2.

As Fig. 3.2 illustrates, the probe's beam position sensitivity increases as a function of beam velocity, beam bunch wavelength, and probe radius. For example, we found on GTA that the 45-mm diameter microstrip-probe's sensitivity to the 425-MHz, 2.5-MeV bunched-beam was actually 85% greater than that of a similar bunched beam whose velocity was near the speed of light. A verification experiment was mounted on GTA during the last portions of the GTA experimental program that included several of the then AOT-division groups (AOT-3, -8, and -10). Both the verification experiment and the theory for these low beam velocity effects are further detailed in papers^{1,2} presented in the 1993 Beam Instrumentation Workshop that AT Division hosted in Santa Fe.

We also provided other improvements to noninterceptive beam diagnostics on GTA. For example, a beam profile measurement technique that was first used on the fusion materials irradiation facility (FMIT) and the Chalk River injector test stand (CRITS) was further improved on GTA by a joint effort of AT-3, -8, and -10. This technique measures the amount of visible light radiating from the beam region from the beam interacting with the residual background gas. Another improvement to GTA beam instrumentation included an addition of a new diagnostic for measuring the beam loss in the intermediate matching section (IMS) that sensed beam current

differences between two places along the beamline. This was used for fast-protection of the IMS and DTL structures. Much of the improved noninterceptive diagnostic instrumentation as well as the interceptive measurements used throughout the GTA experimental program were written up¹ and presented in the 1993 Beam Instrumentation Workshop.

The Diagnostics Team hosted the 1993 Beam Instrumentation Workshop in Santa Fe. Attendance at this annual event was about 130 individuals, representing many accelerator laboratories from the U. S., Europe, and Asia.

The AT-3 beam diagnostics team also supported the design effort for APDF and APT. The APDF effort was primarily split into two segments. The first was to design, install, document, and help commission the diagnostics instrumentation for a dc H^+ injector. We developed an on-line and characterization beam-diagnostic instrumentation plan which was documented in an AOT-3 technical note.³ We designed and started to install the on-line beam instrumentation that consisted of toroids to measure the dc and ac beam current; video monitoring equipment to measure the beam profile parameters; a collimator with calorimetric instrumentation to measure the beam current and power in the halo; and the beamstop calorimetric electronics.

The second segment of the APDF beam diagnostics effort was to develop a beam measurement plan for the rest of the

accelerator. Most of the effort was continued into FY 1994 and was an added effort to the initial design for the APT beam diagnostics plan. We provided primary input to the APT Accelerator Topical Report⁴ which has the conceptual beam diagnostics instrumentation plan for this 200-mA, 1-GeV proton-beam accelerator facility. Our team initiated preliminary designs for several diagnostic beamline devices. These devices included slit and collector transverse emittance measurement devices, video profile diagnostics, microstripline centroid measurements, and wire scanner devices to measure beam profile.

We also complete a beam diagnostics effort for Boeing Aerospace Corporation for a high-average power laser experiment (APLE) in which a very intense electron beam facility was designed to deliver a 40-MeV, 225-mA beam to a wiggler to create a high-average power-free electron laser. The diagnostics instrumentation for measurement of beam transverse and phase centroids was specified in accordance with Boeing's requirements and our ability to meet those requirements. The various mechanical beamline devices were designed and fabricated and the electronics processing systems were designed to the subsystem level complete with block diagrams and subsystem specifications. Five capacitive probes were fabricated. Four probes were characterized and made ready to be shipped to Boeing. These measurements had to be sufficiently adaptive to sense the beam transverse and phase centroids during the operation of the accelerator that only fills every 48th or 144th rf bucket of the 1300-MHz linac. The design was successfully completed that provided the beam information under both of these bunching conditions. The processing electronics design included the electronic systems to be mounted at the probes; the cable requirements; the position/output phase module requirements and general layout; the local oscillator distribution chassis and its requirements; and the system simulator layout including its requirements such as power levels, phase stability, and computer interfaces.

We also completed the delivery and reported on the beam position measurements we provided to the AFEL project within AT division. These measurements were based on button-type image-current probes. We developed the mathematical model describing the signal strengths induced by the beam on each probe lobe and verified this model both with bench and beam tests. We also installed and commissioned the processing electronics and computer algorithms that make up the rest of the complete measurement system. Finally, this work was documented with a paper⁵ submitted to the 1993 PAC in Washington, DC.

We reported in last fiscal year's report about our flying wire beam profile measurement research. During FY 1993 the flying-wire was tested at the APEX accelerator using a ~20 MeV electron beam. The beam detection system and electronics were tested statically by slowly stepping the wires through the path of the beam between macro pulses, mapping out a rough profile of the beam. Full dynamic testing of the motion control and beam detection system was not possible due to the short, ~10 μ s, duration of the APEX macro pulses. The tests at APEX indicated that the collection of the secondary electrons from the wires by a positively biased collector mounted in the bore of the beam pipe provided a cleaner signal than attempting to directly measure the loss of charge from the wires. The profile measured by the flying-wire showed good agreement with video beam profile measurements made immediately up stream of the flying-wire setup. A paper⁶ was presented at the 1993 PAC in Washington DC. Some work was done after the PAC to define the specifications and refine the cost estimates for the APLE project before it was canceled near the end of FY 1993.

Finally, we developed a beam diagnostics and pulsed power plan for the LANSCE II project. This included measurements in both the compressor ring and the various input and output transport lines to the ring. This diagnostics plan was further detailed in the LANSCE II Report.⁷

Magnet Section

Magnetic systems are used throughout particle-beam transport systems, as well as in many other applications (satellites, spectrometers, etc.). Magnets for these applications range in size from very large (more than 1-m aperture and several meters in length) to extremely small (apertures less than 1 cm and approximately 1-cm long). Similarly, the strengths of these magnets vary over orders of magnitude, for example magnetic focusing strengths vary from hundreds of Tesla per meter to a few Gauss per meter. The AT-Division Magnet Design and Measurement Laboratory (MDML) has developed world-renowned expertise in the design, fabrication, procurement, and precision measurement of magnetic devices that span this wide range of applications. We have developed unique expertise in the areas of permanent-magnet applications, very small superconducting magnets, high-order (octupoles, decapoles, dodecapoles, etc.) magnets, precision correction magnets, and cryogenic magnet applications. The MDML has also developed pulsed magnets from sub-microsecond kickers to precision scanning steering magnets used for a variety of applications.

The measurement part of the laboratory, which has been designated a National User Facility, has a broad range of capabilities and instruments for precision measurement of magnetic fields, magnets, and permanent magnet materials. We have developed technologies for precision *in situ* measurement of cryogenic and superconducting magnets with extremely small apertures. Our laboratory has characterized and performed precision measurements of a large range of magnetic fields associated with numerous applications. For example, the MDML has measured accelerator magnets, charged-particle transport magnets, solenoids, precision time-varying steering fields, variable-field permanent-magnet systems, satellite based permanent-magnet systems, magnetic fields associated with electron microscopes, superposed high-order multipole magnets, and ambient or

background fields. Measurement systems used by the MDML include a variety of integral magnetic-field mappers, cryogenic *in situ* mappers, high-precision point mappers, fluxgate magnetometers, NMR probes, and Hall-effect probes.

The staff of the MDML continuously stays abreast of the state-of-the-art in magnetic design and measurement by attending accelerator and magnet conferences, attending advanced accelerator schools and magnet measurement workshops hosted by the United States Particle Accelerator community and CERN. We maintain capability in magnetic field modeling by keeping informed of advances in these codes and attending classes offered by various vendors in the field.

The MDML was primarily focused on supporting the Superconducting Super Collider Laboratory (SSCL) efforts in FY 1993. We applied our expertise in permanent-magnet technology to develop two variable-field permanent-magnet (VFPM) focusing magnet designs for the SSCL. These magnets met the needs of producing a high-quality field with

precision tunability packaged within an extremely physical envelope. The size constraint, in particular, ruled out the possibility of using electromagnets for these applications. Four VFPM quadrupole magnets were completed for the SSCL and characterization of the completed devices showed performance that exceeded specification in every category.

Exotic magnet designs were also created for two new study efforts in AT Division. A conceptual design for a combined-function octupole and duodecapole magnet using permanent-magnets was completed as part of the APT effort. This design incorporated fixed-field octupole and duodecapole core components plus mechanisms to enable small ($\pm 10\%$) and independent variations of the magnitude of each component.

The study to build a new high-intensity pulsed neutron spallation source (LANSCE II) was the second effort requiring conceptual and preliminary designs of numerous magnets, some of which were relatively exotic. These included concepts for a "Lambertson

septum" where one beam path lies within the uniform dipole field of the magnet and a second beam path travels through a field-free region in the yoke of the magnet. Unusual septum magnets were also needed by the optics designers in which a strong dipole field was required on one side of the septum while a weaker field, of opposite sign was required on the other. A preliminary design that met all of the ion-optical requirements was developed and models of the design were simulated with both 2-D and 3-D magnetic field computer codes. The results were very encouraging that this design is indeed feasible.

The need for small, high-gradient, highly radiation resistant magnets for accelerator applications has been steadily growing. Proposed projects such as APT, ATW, ABC specify beam currents orders of magnitude higher than ever-before attained. These high currents not only have the potential for severe irradiation of accelerator components, but also demand highly efficient accelerators to minimize power consumption. A major unknown is whether permanent magnets that meet the criteria for small size and high gradient (far better than electromagnets) are sufficiently radiation resistant to withstand the harsh environment anticipated for these devices. An ongoing program to investigate these questions has resulted in the irradiation of several samples of permanent-magnet materials at the LAMPF beam stop. Neutron fluences up to 10^{21} n/cm² were obtained and measurement of the effect on magnet remanence (strength) is anticipated next fiscal year.

The MDML has also assisted numerous efforts not directly related to accelerator physics during the past year. These efforts included measurement of magnetic fields surrounding a satellite-based permanent-magnet spectrometer and characterization of the ambient magnetic fields around a new electron microscope. One method for precision satellite attitude control is to couple a circulating current to the ambient dipole moment surrounding the satellite. Any stray magnetic fields from the satellite itself

Fig. 3.3. View of VFPMQ with housing removed.

will mask the ambient dipole moment resulting in imprecise attitude control.

A group having recently purchased a state-of-the-art electron microscope requested the assistance of our group to measure fluctuating ambient magnetic fields that were hypothesized to be interfering with their instrument and reducing instrument resolution by more than an order of magnitude. We were able to precisely characterize the ambient fields and determined they were larger than the earth dipole moment, however these were dc in nature and were easily compensated for by the electron microscope. No significant ac field was measured in proximity to the microscope itself. We later determined that the cause of the reduced resolution of the instrument was severe ground loops in the ac power for the instrument.

Mechanical Design, Fabrication, and Assembly Section.

The Department of Defense requested that AT-3 design, build, and test a climbing device (known as the "Gripper," a patent was granted on March 1993) that would enable the user to ascend a vertical steel surface. This project was accomplished by the magnet section and the mechanical design, fabrication and assembly section.

The Gripper was put in for an RD-100 award for 1994.

The beauty of the Gripper is its simplicity and practicality. It is the first magnetic device that allows one to scale any wet or slippery steel structure quickly and quietly or to traverse an overhead surface - like walking on a ceiling. For ascents, the Gripper can be used in several ways: (1) users can wear two hand and two foot grippers for individual climbing (2) the first climber can attach a series of Grippers, leaving them in place as hand- and footholds for others to climb; or (3) light weight graphite ladders can be fastened with Grippers to a surface for easier climbing by rescue workers. A 5-foot-long ladder weighs less than 1 pound and can be attached with 2-foot Grippers (weighing only 3 pounds). A number of

Fig. 3.4. Lattice design for the 1-MW LANSCE II accumulator ring.

the graphite ladders could be positioned as needed. The Gripper also allows one to move sideways or diagonally across steel surfaces: movement is not restricted to fixed hand- and footholds or to the reach of mobile cranes.

In tests done at Los Alamos, a set of four Grippers were used to climb both a smokestack and a bridge crane's vertical support girder. The climbers needed only 5 to 10 minutes of training to master the technique of climbing with the magnet sets. The Gripper is also affordable: mass production of Grippers with molded plastic frames could lower their unit cost to about \$300. The Gripper offers greater mobility in inspecting offshore oil drilling platforms, smokestacks, storage tank interiors and exteriors, the metal superstructures of skyscrapers, or bridges. In short, the Gripper is simple, inexpensive, and offers a whole new mode of human mobility. The Gripper has received notice in the New York Times, Popular Science, New Scientist, DOE - This Month, Mechanical Engineering Magazine of the American

Society of Mechanical Engineers, Discover Magazine, Business Week, the London Times, and the BBC.

We have identified an additional use for this technology. We have proposed an innovative method for temporarily stopping leaks in tanker and bulk carrier vessels. The method relies on the use of permanent-magnet devices that can attach a composite fabric dam to vessel hulls with several tons of force, erecting a barrier to liquid flow. Light weight, modular leak-sealing units can be readily carried aboard maritime vessels or rescue units, enabling quick responses that could simultaneously limit cargo losses and protect the maritime environment. The strength of the composite fabric dam and the powerful adhesion provided by the permanent magnets would allow a variety of liquid and bulk cargoes to be protected by the leak-sealing device: crude oil, kerosene and light-oil fraction, volatile aromatics, fertilizers, bulk and liquid chemicals, and many other valuable and environmentally hazardous substances. This device could readily prove its value to shipping companies, port authorities, salvage operations, maritime rescue personnel, and environmental protection agencies. This device has also received notice in the New York Times, Business Week, and DOE - This Month.

The mechanical design, fabrication, and assembly section also did the design, fabrication, and assembly work for the GTA diagnostics, the SSC variable field permanent magnet quadrupoles, and the Boeing FEL flying wire hardware and beam position monitors.

Collaboration With SSC

During FY 1993, over 20 AT-Division personnel participated in an inter-laboratory arrangement to provide physics and engineering support to the Superconducting Super Collider project in Waxahatchie, Texas. Individuals were assigned to both Accelerator Systems Division (Mechanical Engineering, Controls, and Beam Diagnostics Depts.) and to the Program Office (Linac and Main Collider Groups). The purpose was

to provide SSC with key skills needed to carry out the design and engineering of the 6 accelerators (1 linac and 5 rings). These personnel took up residence in apartments in the Waxahatchie area, and were successfully integrated into the corresponding SSC groups. This exercise was a valuable exercise for our staff, because they were able to work side-by-side with SSC staff members having similar interests and skills, thus providing an exchange of ideas and engineering concepts in accelerator physics and technology. At the same time, SSC benefited by getting a quick infusion of qualified and experienced accelerator physicists, engineers, and technicians not otherwise available. This activity was successful up to the time that the financial support of SSC was terminated. One extremely useful outcome of this collaboration was to identify a new method for the DOE laboratories to work together to maximally utilize our combined resources.

The LANSCE II Initiative

AT-3 played a leading role in the LANSCE II proposal study. LANSCE II is the study of a 1-MW next-generation spallation-neutron source. The scheme utilizes the upgraded LAMPF linac to inject a 1.2-ms pulse of protons into a new accumulator ring. The ring circulation period is 671 ns; hence approximately 1800 turns are accumulated to produce an intense pulse of 1.3×10^{14} protons with 570 ns duration. The pulse is then immediately extracted in a single turn and delivered to the spallation target. AT-3 has been the major contributor to the accumulator-ring design.

LANSCE II Lattice Design and Beam Dynamics. The ring lattice design was influenced by component-placement and beam-optics considerations, with an emphasis on overall simplicity and minimal beam loss. A doublet focusing structure was chosen to provide long drifts, sufficient for placement of the injection chicane with identical straight-injection cells. The second-order-achromatic layout for the arcs allows cells with

properties similar to the straight-section cells, so that the lattice functions of the ring are closely periodic. Additionally, systematic-sextupole errors in the arc dipoles are approximately canceled. The dispersionless straight sections are desirable for placement of the rf system and the injection and extraction systems.

The straight sections house the injection chicane, the bump magnets for injection painting, the large number of bunching cavities, the collimators for beam-halo control, linear and nonlinear corrector elements, and the extraction system. Provision is made for placement of a transverse damper. The achromatic arcs provide room for chromaticity-altering sextupoles and momentum collimators.

For the nominal lattice, we computed the linear lattice functions and the nonlinear ring parameters. After determining minimum stored-beam emittances for the desired space-charge tune shifts, we established the injection-painting algorithm, and worked out a possible extraction-section layout. We computed minimum apertures in all components, conservatively allowing for complete emittance trading between transverse planes, for particles with 1% momentum deviation, and for 10% errors in the lattice functions.

We specified a set of alignment tolerances, computed the maximum likely closed-orbit excursions before closed-orbit correction, and determined the required strengths of the closed-orbit-correcting steerers.

We determined the specifications for the bump magnets that move the closed orbit for injection painting. To control the stored-beam distribution in both transverse planes, there are four horizontal and four vertical bump magnets, located in the long drifts immediately upstream and downstream of the injection chicane. We placed the bump magnets to minimize their strengths while also considering the placement of other ring components, in particular the collimators. The painting uses correlated horizontal and vertical bumps, resulting in

a stored beam of rectangular cross section with a fairly stationary distribution in tune space.

We simulated the injection process, including space-charge forces, using the particle-tracking codes MARYLIE and TLIE. In these simulations, we assumed reasonable errors in the magnetic fields of the main ring magnets. From the computations we obtained scatter plots of the transverse beam distribution, the beam distribution in tune space and the beam distribution in emittance space, as well as the dynamic aperture as a function of momentum deviation. We also obtained information about the number of foil traversals made by particles injected at various times during the injection cycle, with an average of nine foil traversals per particle. We further obtained the distribution of stored-proton foil hits, from which we calculated foil temperature with a thermal-modeling code.

We wrote a program to compute the nonlinear space charge forces for a square distributed (normally a beam is somewhat elliptical) injected beam into the machine. The working point selected for the machine is far enough from the diagonal to reduce the nonlinear x-y coupling from the beam octupole. We also did some benchmarks of the code against a version of Teapot with space charge. We worked on schemes to correct nonlinear resonances due to errors in the ring magnets. In principle "vectors" of correctors can be derived that only act on the real or imaginary part of a particular resonance. This reduces the multidimensional search need to correct the resonances to a series of one-dimensional searches. Or, to put it in a different way, when you correct a resonance you don't at the same time increase the others. Some work was also done on the linear x-y coupling. In general 2 skew quadrupoles are needed if one wants to correct the real and imaginary part of the coupling resonance. If one assumes that the coupling is the result of random quadrupole rolls, then one can compute the ratio of the correctors in advance. The correction of

the coupling in this case can be reduced to a one-parameter search.

Again assuming reasonable errors in the magnetic fields of the main ring magnets, we proposed a correction algorithm employing skew-quadrupole, normal- and skew-octupole, and normal- and skew-decapole correctors. We specified the number of units required and the expected maximum strength for each type of corrector.

We took considerable care in the layout of the injection region, attempting to minimize first-turn losses. The layout allows charge-changing (H^- to H^+) injection and the clean disposal of unstripped and partially stripped beams. An injection chicane, with a three-section 10° center dipole and two 5° septa, displaces the stored beam laterally by some 21 cm at the stripping foil, where the stored and injected beams are joined. The stripping foil is located in the central section of the three-section center dipole.

Placement of the stripping foil in a magnetic field is a novel approach to dealing with the problem of excited-state neutral production and subsequent loss in the ring. In the PSR, this leads to first-turn losses of about 0.25% of the injected beam. By locating the foil in a magnetic field of appropriate strength and distribution, all but about 10^{-5} the excited state population either is sent to a beam dump or is merged with the stored beam. Placing the foil in a magnetic field creates problems with foil heating by the electrons dissociated from the injected beam that return to the foil. However, this problem is to be alleviated by creating a "mirror" magnetic field that serves to deflect the electrons from the foil.

The beam-extraction system consists of a kicker magnet immediately downstream of a straight-section doublet and a septum immediately downstream of the next doublet. We specified the properties of the kicker magnet. We also designed a transport system to carry the beam to the two targets.

LANSCE II Ring Components. We then did sufficient design work on all major components to establish their feasibility. Most components are derived from tested systems, taken from local projects or based on successful designs at other laboratories. A few of the components represent novel or state-of-the-art devices. The ring dipoles, quadrupoles, chromaticity-altering sextupoles and steerers are standard iron-core magnets. We did preliminary designs of the 22.5° , 18-cm-gap dipoles, the 20-cm-aperture straight-section quadrupoles, the 34-cm-aperture arc quadrupoles, the 34-cm-aperture sextupoles and the 20-cm-aperture and 34-cm-aperture steerers.

We also looked at the 20-cm aperture, three-layer Lambertson-type correctors to compensate for skew-quadrupole, octupole (normal and skew), and decapole (normal and skew) magnet errors. These correctors also do not pose a problem.

Preliminary designs indicate that the three magnet types in the injection region, the center dipole, the septum with 8-kG field in the stored-beam channel and 3.5-kG field in the H^- beam channel, and the yokeless quadrupole, are challenging but appear feasible.

The bump magnets appear quite straightforward, and the extraction kicker, while challenging, is feasible. The kicker is a multi-segment ferrite magnet with pulse rise from zero to maximum in about 100 ns and a flat-top of about 500 ns. To minimize beam oscillations due to fields induced in the kicker, we decided to keep the unkicked beam centered in the aperture. To minimize the longitudinal and transverse beam impedances, a metallized ceramic beam pipe is proposed inside the kicker. We looked at the design in enough detail to determine optimum number of modules, the kicker electrical schematic, and kicker impedances.

LANSCE II Ring Diagnostics. Specifications for a complete set of diagnostics were developed. These included systems for monitoring beam loss, the closed-orbit, beam tune, beam current, beam profile, beam halo, extraction efficiency,

beam-phase centroid, beam momentum distribution, and the extent which beam enters the extraction gap. These measurement systems in turn utilize several devices that respond to the beams' electromagnetic signal or interact directly with the beam such as beam position monitors or radiation detectors. Proper functioning of the ring depends crucially on the presence of appropriate diagnostic systems.

Accelerator Technology Development and Training

As stated earlier, our most important assets are our people, and they are regular attendees at the Particle Accelerator Schools, and they are active participants in the LINAC and Particle Accelerator Conferences as well as specialized optics, magnets, and beam diagnostics specialized conferences. The quality revolution has impacted AT-3 and several of our people have attended Edward Deming's "Quality Symposium" via the Laboratory's satellite link. We have also had courses in program development, process improvement, and have an Employee Involvement Team (EIT). These efforts have led to a strong sense of employee empowerment by AT-3 personnel and have instilled a desire to delight the customer.

In October, AT Division hosted the fifth annual Beam Instrumentation Workshop in Santa Fe. The workshop attracted over 130 participants from the U.S., Japan, and Europe. The agenda included invited papers, tutorials, discussion sessions, and poster sessions. The workshop was held in the Picacho Plaza Hotel, which provided an ideal ambiance for a small, informal workshop.

Group members produced and presented numerous technical papers, and several group members have served on conference program planning committees.

Future Plans

Our future plans are to continue the study and proposal for LANSCE II, to provide beam dynamics, diagnostic design, magnet design, and mechanical engineering support for the Accelerator-Driven Transmutation Technologies (APT, ATW, ABC), and support LAMPF operations both with operations support personnel and with improved accelerator diagnostics developed in AOT-2 and AOT-3.

We are heavily involved with the LANSCE 1.5 upgrade project that will greatly improve beam availability to users of the LANSCE facility. This includes diagnostic development and production, design of new beam lines to allow upgrade of radiation shielding, and developing expertise with the Monte-Carlo particle tracking and production codes, LAHET and MCNP, to allow calculation of shielding requirements and electronics in ADTT targets.

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Introduction

FY 1993 saw expansion for Group AT-5. The group grew to 45 people and was responsible for approximately 25% of the Division's budget. AT-5 had over 25 program codes with the Ground Test Accelerator (GTA) remaining as the largest effort.

AT-5 maintained its thrust in providing rf systems for accelerators but expanded in the area of support for ion implantation and materials processing. We assisted Argonne National Laboratory on their Advanced Photon Source (APS), supported Boeing on the Average Power Laser Experiment (APLE) program, supported SSC, and provided the modulator for the Advanced Free-Electron Laser (AFEL) program. AT-5 built the high-voltage modulator for the plasma source ion implantation program in P-Division. While in Los Alamos in May 1993, President Clinton visited this program. We began a program with MST Division to support their efforts in material processing by rebuilding a gyrotron-based material processing system from the Former Soviet Union (FSU). This facility will allow MST to do experiments in the bonding of ceramics with millimeter wave rf.

Our largest program was GTA. AT-5 completed the assembly of 10, 1.2 MW, 850 MHz klystron systems that power the 10 DTL tanks of the accelerator. This system was integrated with a high-voltage capacitor bank and power supply. The system was interfaced with Allen Bradley programmable logic controllers (PLC's) to the EPICs control system. We also assembled the 10 low-level rf (LLRF) systems needed for high-speed feedback control of the rf fields in the accelerator cavities.

AT-5 supported the operation of experimental runs on GTA during FY 1993. We ran the rf amplifiers and LLRF feedback control systems for the RFQ, matching section cavities, and the first DTL tank. All control was from the GTA control room with hands off operation on the amplifiers themselves. This

successful operation of the rf system was a credit to the efforts of AT-5 personnel who designed the rf system.

GTA

High-Power RF (HPRF)

In FY 1994, the production HPRF equipment was almost completed and sighted in MPF-365 on the mezzanine. All major components have been completed and testing is beginning.

The capacitor bank electrical and mechanical fabrication was completed and testing has begun (Fig. 4.1). The Allen Bradley software is complete and integrated into the capacitor bank control rack. This software monitors the state of the capacitor bank and the 5 A, 90-kV power supply and exercises operator initiated control through a T-30 terminal over this equipment. The capacitor bank has two redundant crowbars to protect the klystron loads. All mechanical and electrical drawings on the capacitor room are completed and released. Some drawings still need to be updated to

reflect redlines before the drawing package will be completed.

Five two-hole modulators and control racks are installed on the mezzanine (Fig. 4.2). The modulators have been checked out with high voltage and three have been filled with oil. Ten Thomson klystrons are installed in the modulators. Allen Bradley software for the 5 control racks and user interface terminals has been completed and tested to the maximum extent possible without high voltage. The plumbing and other ancillary support equipment required by each modulator has been completed. The isolators that protect the klystron output cavity has been installed. The waveguide runs from the mezzanine to the accelerating tunnel are completed and the high voltage cables are terminated and installed.

Also in this fiscal year AT-5 operated the rf systems for GTA's experiment 1C repeat and experiment 2A. RF operators supported GTA operations each day from the control room.

Fig. 4.1. GTA Capacitor Bank.

Fig 4.2. GTA modulators and klystrons.

Low-Level RF (LLRF)

The LLRF hardware delivered for GTA in 1993 was primarily for the ten 850-MHz DTL cavities for experiment 2D. A new design of the Input/Output Interface Module that replaced four existing modules condensed the 850-MHz system into a single VXibus chassis. This allowed four LLRF systems per rack, a doubling of equipment density. The designs of all LLRF equipment for GTA are frozen and production drawings are complete. We established commercial fabrication contracts for the VXibus modules, cables, mechanical assemblies, etc. This allowed us to reduce fabrication costs considerably. By the end of the year, 90% of the VXibus modules had been received from the commercial fabrication houses and were undergoing testing. The automated test laboratory that provides functional testing of the individual LLRF devices showed considerable progress. A test, in at least a preliminary form, was implemented using the HP VeeTest software for every VXibus module. The racks to house the ten systems has been completed including the VXibus chassis, the interconnect panels, the internal rack cabling, and the

power conditioning. The reference rack has been modified to provide a total of 16 850-MHz rf reference outputs to support the 9 additional LLRF systems. Lastly, operator manuals for all of the modules were completed to allow understanding, troubleshooting, etc.

In addition, the LLRF section provided operational support for the GTA experiments in January and March. During these experimental runs, data was taken to characterize the performance of the LLRF system which demonstrated very accurate, very stable control (Fig. 4.3). Also, we were able to test the Control Predistorter Module. The device provides a method to decouple the I&Q variables within the feedback control loops. This decoupling allows the feedback gains to be increased to extend the overall system bandwidth. The experiment showed that the Control Predistorter has little effect on the system performance at the low beam currents where cross coupling is minimal. A follow-on experiment should be performed with much higher beam currents in which the I and Q cross-coupling will be significant.

Automated Klystron Test Stand

This year AT-5 used the automated klystron test stand to complete the testing of the two remaining Thomson klystrons. Several improvements were made to the test stand such as expanding the range of the cathode current (14 A to 29 A). Other improvements were made to the LABview program to enhance the user interface. The test stand is currently being used to provide information of efficiency regarding cathode voltage and beam impedance for the AXV projects.

Test of the GTA RF Control System on LAMPF

One of the major hurdles in the control of the rf field inside each accelerating cavity is the need to minimize high-frequency, repetitive transient errors that occur in the field. Different types of control systems can maintain a relatively stable steady-state field. One existing system that can potentially reduce the beam turn-on transients has been implemented on GTA and is being proposed for use on the National Center for Neutron Research (NCNR) linac. This proposed control system is based upon controlling the in-phase and quadrature (I/Q) components of the rf field inside the accelerating cavity. The rf control system now in place on LAMPF controls the amplitude and phase (A/P) of the rf field inside the cavities. There are a number of arguments for using I/Q control rather than A/P, one of them being the adaptive feedforward techniques that have been demonstrated on other programs. An experiment was run on LAMPF as a proof of principle.

The feedforward function is incorporated into the control system by applying adaptive correction signals to the I/Q errors concurrently before the proportional, integral, and differential (PID) control circuitry. Each correction function is computed from the current error signal along with the ensemble of past error functions. Adaptive feedforward techniques have demonstrated reduction in the beam turn-on transients in the cavity field.

Fig. 4.3. Results of LLRF control system on GTA with 46 mA in RFQ.

During the early summer experimental run at LAMPF, the GTA rf control system was substituted for the original LAMPF A/P rf control system on Tank 2 of Module 5 of the CCL. The following are results of the two types of control systems in use with a 26 mA beam inside the cavity. Figure 4.4 shows the results of the I/Q system and Fig. 4.5 shows the results with the amplitude/phase system. Each figure depicts the amplitude and phase errors respectively of the field inside the cavity as measured by the A/P system.

Note that the response of the I/Q control system is faster than that of the A/P control system. In addition, both the amplitude and phase steady-state errors are smaller in magnitude with the I/Q control system. The measurements presented here were made after a minimal setup time. There was not enough experimental time for fine-tuning the system response, yet the data shown are encouraging. It was noted that some design changes must be incorporated in order to successfully utilize the I/Q control system for the NCNR linac. Some

Fig. 4.4. Results of the GTA LLRF control system on LAMPF with feedforward.

Fig. 4.5. Results with the original amplitude/phase control system on LAMPF with feedforward.

of this work includes interfacing the I/Q control system with the existing control software and fast protect system, and accommodating for a high-peak current beam by combining adaptive feedforward with beam feedforward. Applying the I/Q control system to the NCNR linac provides a number of challenges, but performance requirements can be met.

Gyrotron Processing of Materials

AT-5 is supporting MST-4 in the establishment of a Gyrotron based material processing test stand. This program is part of a Cooperative Research and Development Agreement (CRADA) with the National Center for Manufacturing Sciences (NCMS). The test stand and technology was developed at the Paton

Welding Institute in Kiev, Ukraine and delivered to Los Alamos as part of the in-kind contribution by NCMS for collaborative research. AT-5 is marrying the gyrotrons, cryostats, and processing chamber to a high-voltage power supply and computer controls, providing MST-4 with experimental support, developing beam diagnostics, and working with industrial experimentalists to utilize the test stand. In FY 1993 a preliminary form of the test stand was made operational (Fig. 4.6) and engineers from the Paton Welding Institute and gyrotron factory in Nizhny-Novgorod, Russia visited LANL for 3 weeks and operated the 4 gyrotrons that are utilized by the material processing test stand. They also trained AT-5 personnel in the operation of the gyrotrons, alignment of the magnets, and operation of the cryostat. In the upcoming year the processing stand will be completed and industry experimentation will commence.

Argonne Advanced Photon Source (APS)

AT-5 completed the design contract with Argonne to modify some of our existing equipment to operate at 2856 MHz with a higher measurement bandwidth. This included design modifications for the Downconverter, Envelope Detector, and Vector Detector. In addition, we have assisted in the production of hardware for the APS Linac. We fabricated, tested, and delivered 2 Fast Envelope Detector Modules, 2 Monitor Transmitter Modules, 1 Monitor Receiver Module, 1 Downconverter Module, 2 Diagnostic Modules, and 2 Vector Detector Modules. In addition, we supported their effort to assemble 39 modules in Chicago, including providing assembly drawings, part kits, testing facilities, and engineering support. This production effort satisfies the LLRF equipment that Argonne needs for the APS LINAC. In addition, an AT-5 staff member spent one month on a mini sabbatical at Argonne working with the rf Group helping them integrate their LLRF systems with the EPICS software.

Fig. 4.6. Gyrotron test stand. Material processing stand is on left. Tube stand is on right supporting cryostat with gyrotron inserted through cryostat.

Boeing Average Power Laser Experiment (APLE)

In 1993, we put together a system design for the LLRF equipment necessary to support the total Boeing FEL project. This design included minor modifications to the existing 433-MHz LLRF system, a new 433-MHz LLRF system, a new rf reference system, and a new phase-stabilized transport system. Boeing accepted our design proposal and we performed most of this work. We completed the fabrication and test of the hardware for the modifications to their existing LLRF system. These modifications were a result of new system requirements. We complete the fabrication, test, and integration of the new VXIbus-based LLRF system to provide rf field control, resonance control, timing, and diagnostic monitoring for the second klystron that drives two 433.33-MHz cavities. We completed the majority of the rf reference and phase-stabilized transport systems. The work on this project had to stop before completion due to funding changes.

Chalk River Injector Test Stand (CRITS)

AT-5 is participating in setting up a test stand transferred from Chalk River Laboratory in Canada as a cw test stand in MPF-18. The test stand consists of a cw RFQ, a cw injector, and a cw rf system. AT-5 is setting up and operating the rf system. The rf system consists of two klystron transmitters designed by Continental Electronics using EIMAC klystrons. Each transmitter is capable of .25-MW cw at 267 MHz. They have exhibited an efficiency in excess of 70% in their acceptance tests. One transmitter will be used to provide power to the RFQ while the other will be used as test amplifier. The test amplifier will be used to characterize the klystron as a potential cw source for AXY programs. The klystron's high efficiency and its saturation characteristics make it an attractive candidate. Unlike the klystron, the klystron has a soft saturation characteristic and it appears that we would be able to exercise control over the klystron in the high efficiency, saturated.

operating regime. In contrast, the klystron can not be controlled in the high efficiency, saturated operating regime and it is necessary to operate klystrons in the lower efficiency, linear regime to provide control. The characterization we will be conducting on the test amplifier will be the measurement of the transfer characteristic as a function of drive power to determine whether the klystron can be controlled by a low-level control system to control accelerating cavity fields. We will also be doing bandwidth measurements.

The klystron installation in MPF-18 is currently complete (Fig. 4.7) and the low-voltage checkout, meter calibration, and klystron driver checkout is in progress. The high-voltage power supplies are scheduled to be installed in March 1994, and operation will commence shortly after power supply installation.

Directed Energy Weapons Power Integration (DEWPOINT)

During the 1993 calendar year, work has continued in AT Division on the Directed

Energy Weapon Power Integration (DEWPOINT) program. Unfortunately, a substantial decrease in funding has limited the number of technologies that were pursued.

The present mission of the DEWPOINT program has been modified from the original program in which there were dual paths for all critical technologies. The present program has pursued the hyperconducting alternator for the prime power system and a solid-state amplifier for the rf power source.

The prime power for the amplifier will be designed by the Institute of Problems of Electrophysics (IPE) in Russia. The institute has begun to design a hyperconducting alternator to our specification. This past year IPE has been qualifying wire vendors. The initial results suggest that a Ukrainian vendor can achieve a relative resistance ratio (RRR) of 8000 which is much higher than any American vendors. The RRR factor is the resistance ratio of the conductor at room temperature versus the resistance at cryogenic temperatures. The data was confirmed by Texas A&M University. Next year, we will pursue fabricating this

conductor to the proper length with an RRR factor of 8000.

The goals of the rf power program are to design and fabricate a light-weight, state-of-the-art, space-traceable, high-power 500-kW cw rf amplifier. This year Westinghouse-ESG completed the design of a 500-kW, cw amplifier based on the present data of GTE's 1-kW solid-state hybrid amplifier module (HAM) composed of solid-state triodes (SST) and a micro-channel heatsink designed by Lawrence Livermore National Laboratory (LLNL). The specifications on the HAM are: an output power of 1-kW cw, efficiency greater than 65%, and a gain greater than 9d B. In FY 1993 GTE was unable to test a sub module of the HAM that consists of four SSTs and produce greater than 250-W cw because of the drastic changes in the impedance matching circuit at cryogenic temperatures. Thus, DEWPOINT added another task to the Westinghouse contract. The task was to determine if a bipolar junction transistor (BJT) would turn on at cryogenic temperatures. The current belief was that a BJT device would not turn on due to the lack of carrier mobility. However, Westinghouse was able to turn-on their BJT device. The device output had a 150-ms rise time, peak power of 220 W and efficiency of 67% on the first pulse. Due to the success of this task, Westinghouse will begin designing a power amplifier module (6 kW) using the BJTs in 1994. After completing this design, WEC will fabricate a 25-kW cw demonstrator that is derived from the 500-kW space traceable amplifier.

Advanced Free Electron Laser (AFEL)

We have implemented a LLRF system on the AFEL. This system was easily integrated into the AFEL including its software, timing, and rf connections. The Adaptive Feedforward Module has proven to be a valuable and necessary part of the AFEL LLRF system because of the phase noise caused by the pulse-forming network (PFN) ripple. Before the LLRF system was implemented, peak error deviations around 5% and 5 degrees were typical. The LLRF system was able to

Fig. 4.7. 25-kW cw Klystron transmitter installation in MPF-18.

achieve worst-case peak error deviations of 0.15% in amplitude and 0.15 degrees in phase. Figure 4.8 shows the improvements of noise gain in the AFEL system at frequencies above 100 kHz when the feedforward control was added to the feedback control. The amplitude and phase control accuracies of 0.15% and 0.15° were achieved fairly easily, but accuracies around 0.01% and 0.01° have been requested. This requires a careful study of the system to determine and correct any noise sources, time-variances, and other causes of instability. Alterations to the configurations of all AFEL rf components are being evaluated.

AXY Programs

AT-5 has been directly involved in the development of conceptual designs for the various AXY programs. The primary programs thus far are the Accelerator for the Production of Tritium (APT), the Accelerator for Transmutation of Waste (ATW), and the Accelerator Based Conversion of plutonium (ABC).

ATW/ABC

These programs have not had significant funding over the past year, but some work has continued. In particular, in October 1992, AT division sponsored a workshop on ATW and ABC with counterparts from the Former Soviet Union (FSU). In this workshop there was a lively exchange of ideas and the differing viewpoints stimulated a lot of thought and discussion. AT-5 participated throughout the workshop and co-chaired the rf working group.

AT-5 presented a description of possible rf sources which might be appropriate for a system such as this. The rf sources included the klystron, inductive output tube, the multiple beam klystron, and the magnicon. Visitors from the Moscow Radio Technical Institute (MRTI) presented another option, the regotron (Fig. 4.9). The regotron has the potential of generating very high levels of cw power (5-MW or more) from a single tube with multiple outputs (5 to 7). This would mean that fewer tubes would be needed.

Fig. 4.8. Output noise versus frequency in the AFEL with feedback and feedforward control.

Fig. 4.9. Diagram of the regotron amplifier proposed by Russian scientists for the AXY programs.

The regotron has not been tested but is certainly an interesting device concept.

APT

APT provided significant funding over the past year, and progress was made on the details of an APT accelerator. AT-5 was responsible for the conceptual design of the rf system. An industrial partner for the rf system conceptual design was designated (Maxwell Labs, Balboa, CA). Two major subcontractors to Maxwell also made significant contributions to the conceptual design. ABB provided a design for the ac to dc converter, and

Litton Industries helped with the rf generator specifications and operating conditions.

Figure 4.10 shows how much rf power is needed for the APT in the conceptual design. The large amount of rf power has significant impact on the capital and operating costs. Figure 4.11 shows that even with rf generators operating at very close to 60% conversion efficiency (dc to rf), the overall system efficiency (ac power in to beam power out) is only 43.4%.

Cavity Type	Frequency	Number of RF Generators	Total RF Required	RF Capability
RFQ	350 MHz	4	3.64 MW	4 MW
DTL	350 MHz	8	4.9 MW	6 MW
BCDTL	700 MHz	24	22.5 MW	30 MW
CCL	700 MHz	342	223.2 MW	342 MW

Fig. 4.10. RF power requirements for the APT.

Fig. 4.11. Overall operating efficiency of the APT.

The participation by ABB in the study lead to a change in thinking for the design of the ac-dc converters. A typical approach would have been to use many moderate sized converters (say 10 MW) providing dc power to a handful of rf generators. ABB has a lot of experience with dc power transmission, and suggested that a more cost effective approach would be to borrow from the dc power transmission field and use very large ac-dc converters (250 MW). The final design (Fig. 4.12) uses 2 each 250 MW converters and a smaller unit

Fig. 4.12. High-voltage system for the APT.

(15 MW) for the accelerator front end and for module commissioning

Maxwell provided a design for the dc power conditioning and for the rf module layout. Figure 4.13 shows a design of the BCDTL and CCL klystron gallery and tunnel.

Magnicon Study

The magnicon is a deflection-modulated rf amplifier that has been invented by a team in Novosibirsk, Russia, who have been working on deflection amplifiers for some time. The first pulsed device has produced 2.4 MW for short pulses at 915 MHz, with the remarkable efficiency of 73%, which is better than ever achieved with a klystron or klystrode. In addition to the high efficiency, this generator removes energy from the cyclotron motion of the electron beam, and the axial velocity is not disturbed by the output cavity interaction as much as in the klystron case: hence, depressed collectors to further raise the efficiency are a strong possibility.

The Novosibirsk team had previously invented the gyrocon, a similar deflection-modulated amplifier, but the gyrocon was not well suited to accelerator applications because of its small dynamic range and very complicated electron dynamics. The magnicon is said to mitigate these problems, mostly by simpler electron dynamics and the fact that the interaction takes place in an axial magnetic field. The output interaction in the magnicon is generally extended; i.e., it is not limited to

Fig. 4.13. Klystron/accelerator layout for the APT.

90 electrical degrees. This longer output interaction reduces the output cavity fields and losses, and allows more rf power generated before either wall heating or sparking occurs.

Since a higher-efficiency, higher-power rf generator would make the large accelerator projects such as APT, ATW, or ABC much more economical, the magnicon is worth investigating. One of our staff members wrote a large signal magnicon code in partial fulfillment of the PhD requirements at the University of New Mexico. The result of these analyses is an independent check that the Russian claims on the magnicon are true, and that it indeed looks like a very good candidate for driving high-power accelerators. An unexpected bonus from this work is that a simpler type of magnicon, called the uniform field magnicon, was discovered. In the previous designs, a magnetic half cusp, (or a step reduction in the axial magnetic field) was required between the deflection system and the output cavity. Our simulations showed that while the half cusp was no problem to a single-particle simulation of the magnicon, the overall performance dropped very rapidly as the beam size grew to even a few

millimeters radius. The uniform field magnicon retains its performance in our finite beam size simulations up to several millimeters beam size. The results of the two calculations are shown in Table 1.

Another activity in the magnicon area was to invite Dr. Oleg Nezhevenko, the group

Table 1. Comparison of finite beam effects on the half cusp and uniform field magnicons.

Beam radius, mm	Cusp field efficiency, %	Uniform field efficiency, %
~0	86.2	87.9
1	84.1	87.6
2	79.6	86.6
3	75.0	85.0
4	72.8	84.6
5	68.7	84.5
6	63.2	83.7
7	54.5	81.7
8	46.3	80.1
9	39.8	78.3

leader of the magnicon group in Novosibirsk, to Stanford, where he helped with the overall design of a 2.4-MW magnicon at 700 MHz, the frequency of the APT project. Figure 4.14 is a schematic of this design, which could be built in either cw or pulsed versions. Although the cw version is ultimately required for the APT system, the development cost of the pulsed version is much smaller. This design was included in a white paper that was jointly generated by Los Alamos and Stanford to serve as a basis for cooperation in

Fig. 4.14. Diagram of a magnicon amplifier.

magnicon research. An industrial firm has agreed to donate a high-quality electron gun to the magnicon project, and we are pursuing a formal agreement to cooperate. Since the magnicon is still a very new amplifier, it is still a high-risk solution to generation problems. However, after a year of code development, the device still looks very promising for high-power accelerator applications.

Plasma Source Ion Implantation

AT-5 participated in a CRADA with P Division to build a device to process materials using a technique called Plasma Source Ion Implantation (PSII). The intent of the program is to use the ion implantation to modify materials to make the surfaces harder and more corrosion resistant. Three industry-driven applications are the target of the research: nonferrous automobile parts, ferrous tools such as punches and drill bits, and ferrous and nonferrous stamping dies. AT-5's part in the CRADA was to develop the high voltage modulator which "implants" the ions. This modulator was based on the technology developed for the GTA klystron modulators. The modulator has the following parameters: output voltage and current to 100 kV and 25 A, output pulse width to 20 μ s, pulse repetition frequency to 2 kHz. This modulator could deliver up to 90 kW average and 2.25 MW peak to the work piece. The prototype modulator was completed (Fig. 4.15) in FY 1993 and was demonstrated to President Clinton when he visited Los Alamos in May 1993.

Fig. 4.15. President Clinton visiting the modulator for the Plasma Source Ion Implantation device.

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Ground Test Accelerator (GTA) Controls and Commissioning Support

The final checkout and integration of accelerator and beam controls for Experiment 1C was in progress early in 1993. During the early stages of the experiment, it became clear that twenty-four hour operation was required to successfully obtain all the required data. This extended operational schedule was supported with no increase in the total number of controls staff. The control system operation was exceedingly smooth, with no faults reported until after the experimental data had been obtained - when the data disk was filled to capacity and forced a halt in operations.

Several commissioning tools produced for earlier GTA experiments were put to regular use during the various commissioning runs on GTA. The final documentation and user HELP files were completed. These tools include Phase Scan, Low-Energy Beam Transport (LEBT) Steering, Intermediate Matching Section (IMS) Steering, Automated Cavity Conditioning, Automated radio frequency (rf) Calibration, and Video Profile Diagnostic. The latter is a complete diagnostic that provides for profile measurements at the entrance of Drift Tube Linac (DTL) 1.

IMS Steering was not used on GTA because, until just recently, there has not been an agreement on placement of the IMS Beam Position Monitor (BPM) diagnostics. Although LEBT Steering was used quite effectively and routinely in last year's 1B experiment, the redesign of the LEBT to shorten it, caused problems that have been difficult to resolve. As with the IMS, these problems seemed to be connected on the final placement of the various devices in the LEBT. By back-calculating, a set of self-consistent measurements was found. Future validation measurements, steering the beam with one steerer at a time, and comparing these measurements to these simulations, should resolve the remaining problems.

Phase Scan has been used routinely for all of the rf cavities presently installed on the accelerator. This code had one troublesome problem for the operator. The relationship between set-points for rf power (values range from 1.0 to 5.0 typically) and the power actually input to the cavity (values range from 3.0 kW to 85 kW typically) needed to be inserted into the program. An automated rf calibration tool was built to provide that relationship as a table of values and as a second degree equation where the set-point is the dependent variable and the cavity power is the independent variable. This auto-calibration tool was also required for the new automated cavity conditioning tool. This tool will automatically condition a cavity on the accelerator in a hands-off manner, including powering up the rf power source (tetrode or klystron) while recovering from all known conditioning problems.

The Video Diagnostic has evolved from an experimental diagnostic that required specific knowledge to run (usually one of the developers) to a solid diagnostic that most of the GTA commissioning team runs in a routine manner. Several fitting algorithms have been installed to provide for fitting the profiles extracted from the image with unusual sorts of functions. This has become one of the most dependable diagnostics for position in the IMS and the only diagnostic for profile measurements.

Controls Production Efforts for GTA Experiment 2D

A major effort was underway throughout the year to design and install the facility wiring necessary for experiment 2D. During this process numerous enhancements to WIREFLEX, the GTA wiring database tool, were implemented. These enhancements allowed the use of spreadsheet tools - partially automating data entry and providing more convenient use. The streamlining of the data entry allowed more productive use of time and a more aggressive schedule.

Other production efforts included the design and fabrication of the controls equipment racks required for experiment 2D. This task involved the implementation of numerous motion control, feedback channels, temperature sensors, as well as innovative design to keep costs to a minimum.

A major innovation in controls applications was the adaptation of a commercial schematic editor (CAPFAST), an electronic hardware design tool, to create Experimental Physics and Industrial Control System (EPICS) databases graphically. CAPFAST, which supports modular, hierarchical design techniques, will dramatically improve the quality and maintainability of control system databases in the future. The conversion of one of the diagnostic input/output controllers (IOCs) to EPICS using this tool resulted in a concise, clearly documented design.

APDF

The Accelerator Prototype Demonstration Facility (APDF) was a new project this past year. It is sponsored by Defense Nuclear Agency (DNA) and its intent is to ultimately build a high current continuous wave accelerator. This year the focus has been on construction and operation of an injector with a diagnostics box. The program needed to be scaled back when it was determined that there was not enough follow-on funding to build the complete injector and design much of the rest of the accelerator. The control system for the injector was designed and is in the process of fabrication. We have used high-level tools, including CAPFAST, for every aspect of the design. These tools not only make the design more modular and thus easier to understand, but the design information remains on-line so that it can be queried by experimenters or used to produce a hard copy that can be kept for permanent documentation. The control system construction is on schedule and under budget. The costs have been controlled by using surplus equipment that was purchased for other Laboratory projects.

Fig. 5.1. CAPFAST is used for controls database design.

Work for Other Labs

A significant amount of effort was spent providing support for controls efforts at other laboratories. This included EPICS training, help with control system, and database building, and building higher level control tools for use in beam commissioning. The laboratories we supported included Argonne National Laboratory (ANL) on the Advanced Photon Source project, Superconducting Super Collider Laboratory (SSCL), and Continuous Electron Beam Accelerator Facility (CEBAF).

New Project Hardware Development

SSCL LINAC Timing

The AT-8 GTA versa-module European (VME) based timing system was chosen as the basis for the SSCL LINAC timing system. Additional required functionality was identified by AT-8 and SSC, and AT-8 was contracted to implement the design.

The new design is capable of supporting an unlimited number of periodic events with a resolution of 200 nS. Field programmable gate array technology was employed to allow dynamic loading of the hardware. This is the first AT-8 design where the hardware can be reconfigured without removing the device from the VME crate. Another first in this design was the use of an active VME interface connector. This device places the VME bus driver and address decoder on the connector itself, yielding superior electrical performance and improved maintainability.

MVME167 Transition Module

For performance, reliability, and economy reasons, the Motorola MVME167 VME processor module has been adopted as the new standard IOC processor. A companion VME module has been developed to provide the remaining functionality desired and adapt cable pin-outs to existing standards. Additional functionality provided consists of thermal

monitoring circuitry, and several ethernet and RS-232 adaptors. Thermal monitoring circuitry allows software access to the IOC temperature, and provides a hardware set point above which a latching relay device powers down the IOC. Since overheating has been identified as the primary cause of IOC component damage, this feature is expected to result in a significant increase the IOC component reliability. The Ethernet adapters allow the direct connection of either coaxial or optical cables to the module, eliminating the requirement for external transceivers. The RS-232 adaptors interface wire or optical serial communication with the MVME167 processor module.

Step-Motor Control

As the number of external and internal customers of the AT-8 step-motor controllers has increased, incremental design enhancements have improved the performance of this successful system. The automatic braking function has been

improved by the addition of an adjustable delay which allows the brake to fully engage before motor current is removed, and soft ramp up/down has been added to the manual controls. These modifications permit the system to be used in driving high-torque or high-inertia loads, contributing to the continued attractiveness of this motion control solution.

Evaluation of New Hardware

Transient Digitizer

The need for transient digitizers with analog bandwidths of up to 10 MHz has already been felt and is projected to increase in the future. So far, only the Joerger VTR-1 and Omnibyte Comet transient recorders have been used routinely. The 8-bit resolution of the Joergers, and the noise problems of the Comet have not been optimal for several applications including beam jitter and rf feed-forward control studies. This year Joerger, Inc. began manufacturing a four-channel, 5MS/s, 12-bit module. One of these units was purchased and evaluated. Although the module is more expensive than the Comet, it provides 12-bit performance and a superior system interface. The combination of the Comet and the new Joerger unit are a good mix for medium speed transient digitizer applications.

VME LVDT Scanner

A new Linear Variable Differential Transducer (LVDT) scanner module developed by Highland Systems was obtained on loan for evaluation in actuator position feedback applications. This unit would replace a 3U rack of discrete modules, and a VME analog input card - providing 50% cost and real estate savings. The module was found to have acceptable performance, but further work has been deferred due to budget restrictions and an ample inventory of the discrete devices.

Non-Volatile IOC Memory Module

Work has continued utilizing a Force RR-2 VME memory module fitted with 2 MB

of SRAM and an on-board battery for backup to implement a completely self-contained IOC. A file system was created and the board was configured as a RAM-disk. The system has successfully booted vxWorks from the RAM-disk and is planned to be used in this configuration for future applications requiring a completely self-contained diskless IOC which can run with no network resources or whose operating parameters must be maintained even through a power outage.

Talks

Invited talks and seminars were given at Fermilab, CEBAF, SLAC, CERN, DESY, SACLAY and several international conferences. Interest in EPICS and neural-net controllers continues.

EPICS Development and Collaboration

The Experimental Physics and Industrial Control System (EPICS), has provided positive benefits this year to both the scientific communities and to US industrial competitiveness. A technology transfer to three industrial companies was finally completed this year. The EPICS collaboration in the scientific community was also joined by a number of laboratories and universities. The collaboration includes: Los Alamos National Laboratory, Argonne National Laboratory, Lawrence Berkeley Laboratory, Superconducting Super Collider Laboratory, and Duke University.

New members include: CEBAF for the Central Controls for the CEBAF facility, DESY for the Tesla Test Facility, SACLAY for the Tesla Injection LINAC, Duke University extended its use of EPICS to include the MARK III laser, Lawrence Berkeley extended its use of EPICS to include alarm monitors for ALS, The National Optical Astronomy Observatories for the Kitt Peak Observatory, and the Gemini 8 meter telescope, HELSTF/WSMR experimental facility at the White Sands Missile Range, Allied Signal Aerospace for the agile manufacturing facility, and Creighton University and Kent State University for the STAR detector for RHIC.

The EPICS software has had considerable contributions from several institutions this past year. Graphical database definition is supported through the addition of a EDIF filter which allows database definition using a commercially available schematic capture tool, CAPFAST. A MOTIF-based display editor and configuration tool, database graphical link editor, alarm configuration tool and knob manager have also been added. Extensions to the core software include an ASCII loadable format for the real-time database. Reliability improvements were made in the communications area to support

channel access client connections of thousands of signals.

Three industrial companies have been licensed to extend and distribute EPICS technology in the private sector: Kinetic Systems, Tate Integrated Systems, and Titan Kinetic Systems is marketing the EPICS software, with their extensions, as a software product called Intuit. Tate Integrated Systems is marketing the EPICS software, with their extensions, as TIS-4000 integrated. The industrial companies have delivered over \$3 million in control systems for water distribution, waste water collection, data acquisition, natural gas liquefaction and semiconductor manufacturing.

Electronic Computer Aided Design (ECAD) Support

The Electronic Computer Aided Design (ECAD) effort this past year included supporting the diagnostics design requirements of AT-3, the low-level and high-power rf design requirements of AT-5, and the controls hardware development requirements of AT-8. The bulk of this support effort was to design printed circuit boards and associated hardware for AT-5 and AT-8. ECAD also continued design efforts in the area of electro-mechanical packaging and documentation. This included the layout and design of low-level VME Extended Interface, VME External Interface (VXI) printed circuit board module and sub-module assemblies. VXI mechanical module templates were used to aid in the documentation of each

type. Mechanical packaging and documentation was done using Autocad CAD software. Additional documentation produced included system wiring diagrams and updated drawings per Engineering Change Requests.

An extensive customized parts library for printed circuit board design and documentation increased in the variety of parts supported. This library ensures consistency in design among many ECAD designers. It also supplies as much useful and relevant information as possible for the parts list extraction process. Parts lists extracted from each design includes a description of the part, its reference designation, manufacturers part number, and the name of the manufacturer. Library maintenance was expanded to include a quick access local archive disk containing all completed ECAD files. All electronics packaging and design efforts were done using Intergraph electronics ECAD software.

The section placed 25 printed circuit board fabrication orders, which amounted to more than 400 delivered boards. These orders were placed using a blanket purchase order agreement developed with MAT-9.

Computing Support

Responsibility for operation and maintenance of the AT-Division network rests with the AT-8 computing support section. The section strives to maintain

high-quality network services in a heterogeneous computing environment using modern, proven technology. The AT-Division network has over 100 workstations, over 200 personal computers (IBM and Macintosh), approximately 15 VAX computers, and several network file servers on four open, unclassified 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 section is responsible for complying with various Laboratory and DOE policies and orders for multi-user open computing.

These 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, accelerator physics design, 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). A common electronic mail system supports all users on the networks.

Most of these networks uses a combination of fiber optic technology and a hub concept that eliminate most of the problems caused by lightning strikes and incorrect termination of network cables by users. Network problems are easily

diagnosed through a PC-based system that communicates with remote network equipment.

During the past year the computer support section reduced maintenance and operating costs of the VAX, Sun, and CAD systems. This cost reduction resulted primarily from three factors. First, we phased out older machines that have a higher yearly maintenance charge. Second, some non-critical hardware maintenance contracts were eliminated, and the maintenance was accomplished on a time and materials basis. Finally, all software maintenance contracts were reviewed, and reduced.

The network system managers installed new operating systems on all the workstations and file servers and upgraded many of the applications software packages. New services included a connection to the the World Wide Web and coordination with C Division to register AT-Division personnel on the Laboratory-wide Electronic Mail Registration system.

A major accomplishment in FY 1993 was the decommissioning of the "Q" and "L" classified networks. The procedures for decommissioning were carefully planned and executed, with frequent communication with the users and OS-4, so that little or no disruption in computing service resulted.

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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 1993 has been successful for AT-9. One of our teams received the Laboratory's Distinguished Performance

award for experimentally demonstrating the principle behind the operation of the gyrotron amplifier. The gyrotron is a high-power microwave source with potential application for the NLC. This effort was led by Dr. Ray Stringfield, an AT-9 staff member. Another staff member, John Kinross-Wright received a Distinguished Performance Award for his participation in bringing about successful lasing of the AFEL.

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. This machine will allow energetic electron collisions to be studied at much higher energies than currently possible at Stanford Linear Collider (SLC) or 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 (RKA)

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. 6.1). The buncher section, which consists of the input and idler cavities, has

RELATIVISTIC KLYSTRON PERFORMANCE GOALS

POWER = 1 GW
PULSE LENGTH = 1 μ s
ENERGY/PULSE = 1 kJ
EFFICIENCY = 35 %

BEAM VOLTAGE = 600 kV
BEAM CURRENT = 5 kA
PRF = 5 Hz
FREQ = 1.3 GHz

Fig. 6.1. Schematic drawing of relativistic klystron amplifier.

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 designing a totally new output cavity. The new design addresses the electron reflection problem and beam matching.

Peak powers approaching 500 MW at 1.3 GHz have been produced in pulses of 1 μ s nominal baseline-to-baseline duration. The half power pulse width is 9.5 ms. These pulses contain an energy of about 160 J. Rf output begins on the rising portion of the current pulse and terminates just before the highest part of the pulsed power curve is reached.

Three-dimensional cavity modeling has proven to be critical for designing the very low Q output cavity needed for converting the low impedance modulated electron beam to microwaves. The thrust will be to increase the output power to 1 GW and to widen the pulse to 1 ms.

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 at the outer diameter, couples power into a low-impedance coaxial transmission line. The coax tapers out into standard 6 inch 50 Ω line in which power is measured with a directional coupler and then dissipated in a dummy load.

The input cavity of the RKA uses a waveguide input with iris coupling to accommodate a maximum drive power of 300 kW (Fig. 6.2).

Fig. 6.2. RKA input cavity design.

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. 6.3.

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. 6.4, the input cavity is easily capable of producing 10% modulation with only 200 kW of injected rf power.

Idler Cavity. The role of the idler cavity is to substantially increase the beam modulation that is initiated by the input cavity. The idler cavity is placed at the

position downstream of the input cavity where the beam modulation reaches its highest value, which is where I_1/I_0 is about 10%. The idler cavity can be

Fig. 6.3. Theoretical (lower) and experimental power reflected at the input cavity.

inductively tuned over about 100 MHz, from 1300 to 1400 MHz. Conventional klystrons use several idler cavities and can afford to sacrifice individual cavity gain and yet still achieve a high-beam modulation by tuning the cavities far off resonance. Since the RKA had only one idler cavity for these experiments, we require high gain and tune the idler close to the drive frequency. Measurements

Fig 6.4. Current modulation downstream of input cavity as a function of rf input power.

were made of beam harmonic current modulation (I_1) as the rf input power was varied and as the idler cavity tuning was changed. The harmonic current clearly increases, as predicted, as the idler cavity tuning moves toward the 1.30 GHz rf drive frequency for a given amount of input drive. We could not adjust the original idler cavity frequency any closer than 1344 MHz because the peak surface field at the idler cavity gap exceeded the level for rf breakdown. Rf breakdown across the idler cavity gap was encountered when the input drive power was increased in order to increase the beam modulation and when tuning the idler cavity near the magnetron drive frequency. The rf breakdown caused a major disruption of the beam modulation.

We disassembled the idler cavity for visual inspection. The reentrant nose and the opposite side of the gap showed strong evidence of arcing. To solve this problem the reentrant nose of the idler cavity was replaced by one with a much larger radius of curvature in order to reduce the peak surface field. The original reentrant nose was simply the rounded edge of the 0.065-in-thick beam drift pipe. The modified nose had a radius of 0.1 in. The gap of the idler cavity was increased to offset the increase in capacitance due to the larger radius nose, and bring the resonant frequency of the cavity back to near the original design.

Beam modulation data were taken for

Beam Modulation After the Idler Cavity

Fig. 6.5. Beam modulation versus rf input drive power.

Beam Current (I_0) and Modulated Beam Current (I_1) for the Modified Idler Cavity

Fig. 6.6. Beam current (I_0) and modulated beam current (I_1) for shot 1516

different idler tuning frequencies and input cavity drive powers to find the best combination for maximum beam modulation for the original idler cavity. The data showing beam modulation (I_1/I_0), at the location of the output cavity gap, as a function of input drive power is plotted in Fig. 6.5.

The data showing the beam modulation as a function of idler cavity tuning is somewhat incomplete because we installed the output cavity as soon as it was available.

From PIC code simulations, the amount of modulated current out of the idler cavity for maximum output was determined to be 65-75%. In Fig. 6.6,

the beam current (I_0) and the detected signal (I_1) from a B-dot probe located 22 cm downstream of the modified idler cavity prior to the installation of the output cavity are shown.

The modulation of the beam is over 60% for most of the pulse length. The amount of extractable beam power is usually given as $P = (V \times I_1)/2$. For this case with an average voltage of 650 kV and an average harmonic current of 3.2 kA, about 1 GW of extractable power is in the fundamental harmonic. All of the kinetic energy associated with the modulated beam cannot be extracted because of the effect of the space charge potential depression.¹ Therefore, the output cavity can only extract about 70% of this power, and should produce 700 MW of rf output power or 700 J per pulse.

Output Cavity Development

The Modified Output Cavity. To date the highest energy obtained with the modified output cavity, in single pulses, has been 160 J. Data are shown in Fig 6.7 where rf output power, beam voltage, and beam current are all overlaid on the same time scale.

The peak power is 375 MW. Note that the rf power goes away before the beam power reaches its maximum value. This will be discussed later. The frequency down-converted mixer IF signal from this shot, shown in Fig. 6.8, is relatively clean. The FFT of the mixer signal is shown on the right.

The 3 dB bandwidth is 0.9 MHz. Other shots have recorded higher peak powers, although at a slightly lower energy per pulse. The signals from the two B-dot loops located 90 degrees apart on the upstream wall of the output cavity are shown in Fig. 6.9.

They track together indicating that the output cavity is operating in the proper mode. The B-dot signals are plotted in Fig. 6.9 in terms of the output cavity gap voltage they represent. The actual voltage across the 2.76 cm output gap at 375 MW reaches 370 kV producing an average

Overlay of Output Power, Beam Voltage, and Beam Current

Fig. 6.7. Beam voltage, current, and output power for shot 1308.

IF Output from the Mixer Showing Frequency Stability of the RKA Output over 1.2 μs

Fig. 6.8. Downconverted mixer signal from the output of shot 1308, L.O. = 1280 MHz.

Output Cavity Gap Voltage Determined from Two Cavity B-Dots

Fig. 6.9. Output cavity gap voltage determined from two cavity B-dots.

electric field of about 134 kV/cm. The output cavity has been modeled with a three-dimensional rf structures simulator program, known as the High-Frequency Structure Simulator (HFSS).² From the HFSS simulation, the magnitude of the peak gap voltage, if 500 MW is being coupled into the output coax, was determined to be as high as 538 kV across the geometrical cavity gap with a peak surface electric field of 225 kV/cm. This gap voltage was high enough to turn electrons around in the beam. Therefore, it was clear that the modified output cavity would never be able to reach the desired output power level of 1 GW.

At this point it is not yet certain why the rf pulse is terminating prematurely. The most reasonable explanation at this time is that the output cavity is producing fields high enough to reflect electrons back up the beamline and/or start some oscillation phenomenon such as a virtual cathode. Figure 6.10 shows traces representing magnetron forward and reflected power, the B-dot loop signal in the idler cavity, and the B-dot signal in the input cavity.

All of these signals have a spike at the time the rf output power goes away. These signals are bandpass filtered with a bandwidth of several hundred MHz around 1.3 GHz, so the spike appears to be the result of an rf modulation on the beam (space charge wave) traveling back up the beam toward the cathode. The interpretation of the observation is complicated by the fact that the output

cavity gap appears to be breaking down at this time as well.

New Output Cavity Design We realized, with the help of the ISIS simulations, that bunching the beam too strongly ($I_1/I_0 > 1$) would result in an unacceptable loss of beam kinetic energy due to the increased potential depression associated with the much higher space charge of the fundamental harmonic current. Instead, the ideal beam modulation appeared to be about 65%. To extract this energy efficiently requires an output cavity with a loaded Q of about 4, a factor of two higher than originally predicted. This is primarily because the harmonic beam impedance is lower at 65% modulation necessitating a lower output cavity shunt impedance for good conversion efficiency. A completely new output cavity with a lower loaded Q has been designed using HFSS. The ability to do realistic 3-D electromagnetic modeling is proving to be critical for developing new, realistic output cavity designs. An output cavity is a true three-dimensional problem with traveling wave boundary conditions. Other than HFSS, to our knowledge there is no other computational code available that can solve 3-D problems with traveling wave boundary conditions in the frequency domain, although MAFLA can address similar problems in the time domain. The new output cavity will have a lower output gap voltage, thereby reducing the probability for electron reflection and rf breakdown across the gap. For an output power of 500 MW, the geometrical gap

voltage is calculated to be 365 kV and the peak surface field is 246 kV/cm. The peak surface field has not increased substantially over the value in the modified original cavity, but the gap voltage has been drastically decreased. The peak surface field is what causes the rf breakdown, while electron reflection is determined by the line integral of the electric field along the electron trajectory across the geometrical output gap and the fringing fields just inside the drift pipe flanking the gap. The lower gap voltage should allow the new cavity to consistently extract 0.5 GW or more for the microsecond-long beam pulse.

The adjustable tuning, output loading, and gap length features in the original output cavity were not useful because the output loading could not be made strong enough, even by machining most of the vanes away to open the irises almost completely. The new design has dropped most of the adjustable features of the original design in favor of creating a cavity specialized for extracting the high-modulated power present on the very low-impedance beam. A very low-cavity shunt impedance is necessary to efficiently couple to the low-impedance beam.

The new pillbox-shaped cavity has a considerably smaller outside diameter which will make the cavity less likely to induce virtual cathode formation caused by the large space-charge bunches passing through the gap. The decreased Q will help prevent the cavity fields from reaching the point where electrons are reflected. The coupling slots have been increased in both height and angular width. There is no variable coupling adjustment, and the tuning slug has also been eliminated. A separate tuning control is usually desirable, but the only available location would put the tuning slug in the position where the magnetic field is strongest (near the cavity's outer wall) and this is the location desired for the output coupling irises. The one adjustment that has been retained is the gap length, which can tune the frequency to some extent. Views of the new design are shown in Fig. 6.11.

Input and Idler Cavity Gap Voltages with Magnetron Power Overlay

Fig. 6.10. Input and idler cavity gap voltages with magnetron power for shot 1308.

Fig. 6.11. Cross-sectional and end views of the new output cavity.

The end view only shows one-half of the structure because, due to symmetry, it was not necessary to model the complete structure. An electric-field probe has been added on the right side for modeling purposes to supply an input signal. The beam passes from right to left. The output cavity section is coupled to the low-impedance coaxial line through 4 irises defined by 4 posts. The output coax then tapers to the standard 6-in.-diam., 50W line dimensions. This cavity has a resonant frequency of 1300 MHz and a loaded Q of about 4.1 according to HFSS.

Cold test results from measuring the new cavity are shown in Fig. 6.12. After smoothing the ripple from the B-Dot response, it is clear that the cavity is oscillating essentially as designed.

The new cavity has been installed and is presently being tested at low power. The lower Q of the new output cavity has dropped the gain of the RKA to about 26 dB. Some of this gain loss will be recoverable by tuning the idler closer to the operating frequency. We will

Cold test of the New Output Cavity

Fig. 6.12. Cold test of the new output cavity.

gradually increase the drive power to condition the output cavity for operation at full power within the next two months.

Large Orbit Gyrotron

Proof of principle of the LOG amplifier was accomplished in FY 1993. The ultimate power output goal is 500 MW with a gain of at least 20 dB. Future applications includes use as a source for the NLC.

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, non rotating 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. 6.13, employs a cylindrical

Fig. 6.13. Schematic drawing of large-orbit gyrotron amplifier.

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.

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. 6.14). 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. 6.15. 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.

Fig. 6.14. Electron gun and beam optics synthesized using computer modeling.

Fig. 6.15. Three-dimensional ISIS calculation of electron trajectories including dc and ac fields.

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 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. 6.16. 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 has been performed using the electromagnetic field solving code MAFIA, analytic modeling, and cold-test measurements performed with a vector network analyzer. Figure 6.17 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. Fig. 6.18 shows

Fig. 6.16. Beam voltage and current from a typical gyrotron shot. Input beam power to gyrotron is 2.4 GW.

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.

We evaluate amplifier performance by comparing the radiated microwave power in three different circumstances. First, the

Fig. 6.17. Measured mode spectrum of gyrotron resonant structure. The strong peak at 1286 MHz is the desired operating point.

Fig. 6.18. MAFIA output showing electric field distribution of 3-field symmetric mode at 1277 MHz.

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.

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 thyratron 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- μ s pulse. It is being used as the electron-beam driver for the RKA experiment and as a thyratron test bed (Fig. 6.19).

Portable Pulser

The portable pulser is another advanced modulator developed for HPM source experiments. The pulser is currently undergoing commissioning in building MPF-14. When in operation, the machine will deliver a 600-kV, 3 K-pulse. This unit will be available in FY 1994 as a test bed for GYROTRON, RKA, or other source development.

Fig. 6.19. BANSHEE pulser with RKA experiment in place.

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. GPR experiments are ongoing at TA-49 and other lab sites. The system has been successful in locating buried materials in support of the Lab's environmental restoration program.

Electron-Gun Test Stand

An electron gun test stand, a 200-kV, 200-A, 15-Hz high-voltage modulator used for developing and testing electron-gun components is near completion. 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 4 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. 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 HPM Vulnerability Committee.

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.

Advanced Free-Electron Laser Project

AT-9 continued our contribution to the AFEL project in 1993. In addition to supplying the 1300-MHz rf power for the experiments underway and assisting with the experimental program, we began construction of a new higher power and compact rf station dedicated to the AFEL project. This new effort is a collaboration between AT-17, AT-5, and AT-9. The rf station capitalizes on the hardware and expertise available in AT-9 at 1300 MHz to substantially improve the capability of the AFEL. The performance goals include greater power, longer pulse width, and higher repetition rate. The system will be smaller, more reliable and computer controlled as well. We have also worked closely with AT-5 during the year to integrate a state-of-the-art low-level rf control system into the experiment. During the course of the year, the existing klystron was replaced with a different model, allowing a pulse length increase and improved reliability. The collaboration between the groups will continue into 1994 with the completion of the new rf system and final shakedown of the LLRF. These achievements should allow the AFEL to produce 100 watts of optical output.

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AT-10 GTA Installation, Commissioning and Operations

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Introduction

With the Laboratory reorganization and the merging of the MP and AT divisions into the AOT division, AT-10 was renamed AOT-10 on November 8, 1993. Most of the references to a group number in the following text refers to AT-10, which was appropriate for all of fiscal year 1993.

A large fraction of AT-10's work was in support of the Ground Test Accelerator (GTA). However, in preparation for expected new programs, an increasing effort was devoted to the design and assembly of a cw proton injector test stand. We succeeded in moving a complete operational cw injector test stand to Los Alamos and are in the process of designing and assembling a new, higher-performance injector suitable for several proposed programs. During the year, we did final assembly and initial testing on a cw H^+ ion source, as part of the NPB (Neutral Particle Beam) program.

Because of rapidly changing funding during this year, a number of people supported several different projects outside AT division. A sampling of these smaller tasks included:

- design and assembly assistance at the SSC (Superconducting Super Collider),
- calibration of a large backlog of oscilloscopes and other electronics,
- design of a stand-alone control and data acquisition system for plutonium processing,
- experimental support on the study of high-power microwave effects, and
- continued assistance with a DARHT (Dual-Axis Radiographic Hydro-Test) prototype.

Background

AT-10 contributed to GTA in three major areas. It was our team's responsibility to plan, execute, and evaluate all GTA beam commissioning experiments. We also planned, coordinated, and supported the installation of GTA hardware. In addition, we were responsible for the GTA facility and its management, modification, maintenance, and operation.

AT-10 worked with the GTA project office to plan and coordinate activities of the five AT groups that contributed to GTA installation.

AT-10 determines what experiments are required to confirm that all accelerator components perform as designed and that measured beams agree with simulations and meet design criteria and programmatic needs. As we commission progressively more of the complete accelerator, we ascertain the different diagnostics, controls, simulations, rf, and beam parameters that are required. During experiments, we coordinate division resources to execute the plan, schedule the personnel, and provide daily guidance.

After experiment completion, AT-10 coordinates the post-experiment efforts and provides the majority of the analysis and interpretation of the experimental results. Post-experiment analysis attempts to understand any disagreements between actual performance and predictions, to verify that beam diagnostics are performing correctly, and to confirm that accelerator operating conditions produce the desired beams.

The injector development section of AT-10 has prepared new designs for both high-brightness H^+ injectors and high-current, cw H^+ injectors. We have worked hard for several years to have operational cw hardware on which beam experiments could be made.

Accomplishments

GTA Project

During the past year, we completed two major commissioning experiments. In experiment 2A, we characterized operation of the first drift-tube linac (DTL) module. The second experiment 1C extension involved more detailed tests of the intertank matching section (IMS) operation and its control of the beam characteristics. We also measured the performance of prototypes of the DTL microstrips. Microstrips are also called beam position monitors (BPM)s.

In one of the first experiment 2A tests, we determined the correct operating DTL rf amplitude and phase setpoints by comparing phase scans with simulations. A phase scan measures the output-beam energy and phase centroids versus input beam phase at a particular DTL gap voltage. Figure 7.1 shows measured phase-scan data for different DTL gap voltages. The slope of the center, linear region of each data set in Fig. 7.1 is proportional to the DTL total phase advance, a function of gap voltage. Measured and predicted slopes versus gap voltages are used to determine the correct operating gap voltage and cavity power level. We independently determined the gap voltage versus power by measuring the end-point energy of gap-originated x-rays. Gap voltage, determined from x-ray measurements, agreed within 1.4% of the power level with the correct phase-scan slope. Using SUPERFISH and the measured Q, we predicted the relationship between gap voltage and power, and found agreement within 0.4% to the x-ray measurement.

We examined DTL longitudinal-beam dynamics by relating the input- and

Normalized Energy vs Relative Beam Phase for DTL Module #1 (Data)

Fig. 7.1. Measured phase-scan data for different DTL gap voltages.

output-beam energy and phase with a transfer matrix. We varied the input DTL rf drive phase directly and varied the DTL beam input energy by changing the IMS buncher phase. Using LINDA, we measured the resulting output-beam phase and energy, to obtain excellent agreement with three of the four matrix elements when compared to PARMILA predictions. This comparison indicated we were operating at a DTL gap voltage slightly less than design.

The measured output-beam longitudinal emittance was found to be in good agreement with simulations.

To understand the transverse focusing properties, we measured the transverse characteristics of the DTL output beam for a variety of input conditions. Using an empirical IMS beam-steering model, we varied input-beam position and angle, while measuring output-beam position and angle. As described above, these data will be used to evaluate the transverse transfer matrix. Using the IMS focusing model, we adjusted the IMS variable-field quadrupoles (VFQs) to produce different beam-emittance shapes (tunes) at the DTL entrance. The DTL output beam showed little change in shape in spite of significant changes in IMS tune. This unexpected result was the impetus for experiment 1C extension, where we attempted to verify that different IMS tunes produced significant DTL input-beam changes. The measured DTL output-beam shape agreed with prediction and was suitable for the following linac structures. This finding successfully fulfilled a major milestone.

Good transmission and maximum beam in target requires constant beam centroid and emittance shape during the entire macro-beam pulse. These observed parameters were constant except during the initial few tens of microseconds. Our measurements showed that the DTL imparted no emittance growth to the beam.

In a final test, we operated the GTA RFQ with the design 2-ms, pulse-length beam. Due to refrigerator capacity limits, rf

power was supplied only to the RFQ; however, all rf structures had been previously operated without beam for the required 2 ms. In all cases, behavior was normal during long-pulse operation. For experiment 1C extension, we removed the DTL module and reinstalled the beam diagnostics at the end of the IMS. We observed that space charge causes the mismatch factor (the measure of emittance shape change) to change along the beamline. Therefore, for a particular IMS tune, a beam with a large mismatch factor at the emittance station won't necessarily have a large mismatch factor at the upstream location of the DTL entrance. For each of the various tunes we will need to estimate what the measured beam emittances would be at the entrance of the DTL and then simulate the acceleration of these beams through the DTL #1. These DTL output beams will be compared for emittance shape changes. We expect these simulations to agree with our previous observations. In any case, comparing measurements and simulations will either confirm or correct the IMS model.

In the second part of 1C extension, we successfully tested BPM prototypes that will be located between DTL modules. Positions recorded by the BPM units faithfully tracked beam positions measured by the emittance gear. In another test, we confirmed that the beam positions measured by one of the IMS BPMs also tracked the positions predicted by the emittance measurements, but with a small disagreement in absolute value. Position measurements made by the other two IMS BPMs cannot be independently confirmed by a separate device. At a later date, we will use our BPM measurements to determine if these beam positions can be used to predict the beam position and angle at the entrance of the DTL.

AT-10 is responsible for the injector operation and characterization during the commissioning of downstream GTA components. During this past year, we improved source performance to produce 70 mA of quiet beam used to further verify RFQ performance. With the injector rolled back from the RFQ and

with an emittance station positioned at the RFQ entrance, we produced an empirical map of Courant-Snyder parameters versus the two LEBT focusing-solenoid currents. With the injector in place, we maximized the RFQ transmission by varying the LEBT solenoids in a two-dimensional grid search. The solenoid currents giving the best transmission also produced the design Courant-Snyder parameters, further validating the RFQ design.

To support future on-line component commissioning, AT-10 conducts the high-power rf conditioning and characterization of the DTL modules. During the past year, two additional DTL modules were high-power conditioned to 120% of design power levels for a 2-ms pulse length at 5 Hz. Typical cryogenic Q enhancement values of 3.4 are observed after the modules are conditioned at high power.

All GTA rf structures are operated at cryogenic temperature, requiring that the accelerator reside inside large vacuum vessels, whose typical diameters and lengths are 1.2 m and 5 m, respectively. We ensure vacuum integrity of these large vessels and install and maintain all vacuum systems. In Fig. 7.2 we show the vacuum vessels, which contain the RFQ and a DTL module, installed on the beamline during experiment 2A. Figure 7.3 shows one vacuum vessel with five DTL modules installed in their final positions. We also operate and maintain the 750 W refrigerators during commissioning and other off-line cryogenic testing.

AT-10 personnel align all beamline components during assembly and beamline installation. Drift tubes are aligned with respect to other drift tubes in each module using the taut-wire technique. At room temperature, we obtained sub-mil accuracy of drift-tube transverse positions and 0.25-degree accuracy on the roll angles. In Fig. 7.4 we show one of the DTL modules installed in the taut-wire measurement assembly. Using a similar taut-wire procedure, we in situ checked alignment, field strengths and programmed movement of the IMS quadrupoles at both

Fig. 7.2. GTA configuration for Exp. 2A.

Fig. 7.3. Vacuum vessel with five DTL modules installed in their final positions.

room and cryogenic temperatures. We completed most of the design for the facility ac power wiring; the high-voltage power for the rf system; the I&C wiring for the rf, actuators and vacuum systems; switchgear for the numerous motors; and the I&C wiring for the 40-kW cooling plant. We planned and installed the rf

waveguide for the expected 24-MeV accelerator configuration. AT-10 also has the responsibility for the installation and maintenance of the GTA building air, nitrogen, gas alarms, water cooling, and lighting systems. In expectation of the 24-MeV operation, we directed installation of a steel floor

over the waveguide basement. Because this structure supports all DTL modules and a diagnostic beamline, very tight tolerances are required on deflection and vibrational stability to maintain DTL alignment.

CRITS Project

Funding for the setup of the Chalk River Injector Test Stand (CRITS) was provided by two separate sources: internal Laboratory funding¹ and defense conversion moneys from the Defense Nuclear Agency. These activities commenced in October 1992, and were completed in May 1993 when the Chalk River Laboratory (CRL) equipment was delivered to Los Alamos. DNA funding arrived in June 1993, and has been used for modifying and installing the 50-keV ion source, LEPT, RFQ, and 267-MHz klystron system in MPF-18. The RFQ was designed for 50 mA, with a 75-mA space-charge limit.

In October 1992, we collaborated with Chalk River personnel on an ion-extraction experiment at CRL. Figure 7.5 shows a sample result on emittance and divergence from that work. Meanwhile, we collaborated with Jack Boers (Thunderbird Simulations) to include axial magnetic fields and projectional emittance to the SNOW extraction code. Analysis of the CRL-LANL data in terms of these effects has been initiated, but no conclusions have been drawn. Emission-aperture shaping has certainly effected the measured-beam emittances and divergence. This result suggests that the ion-extraction optics is not being dominated by the ≈ 875 G axial magnetic field.

Several of our personnel participated in the final operations of the CRL RFQ1 project. During this time several

milestones were made in the cw rf linac arena:

- An RFQ was operated in cw mode with klystron tubes. This was accomplished by a collaboration of Continental, EIMAC, CRL, and LANL personnel.

Fig. 7.4 DTL module installed in the taut-wire measurement assembly.

Fig. 7.5. Emittance (A) and divergence (B) results from the collaborative ion source extraction experiment completed with CRL. At the design perveance for the new 75 keV injector improved performance is noted for both beam emittance and divergence.

- Protection circuits were designed and partly implemented by LANL and CRL personnel. Without adequate protection, the RFQ drive loop can be destroyed in a matter of milliseconds by sustained arc-downs.
- The cw RFQ produced a 1250-keV and 52-mA accelerated beam during these klystrone tests. Normalized rms emittance was 0.49 (π -mm-mrad).

During the RFQ measurements, typical 50-keV injector-beam currents were 70-75 mA from a 7-mm extraction gap and 5-mm diam emission aperture. A typical Reticon beam profile obtained during injector operations is shown in Fig. 7.6. A Gaussian fit is superimposed on the Reticon data. Figure 7.7 shows the measured full-width-at-half-maximum (FWHM) beam profiles as a function of beam energy for the electron-cyclotron resonance ion source (ECRIS) operating at 760-W power.

While the RFQ1 equipment was being shipped to Los Alamos, we analyzed the CRL single-solenoid LEBT using SNOW-generated beam parameters as input to the TRACE LEBT calculations and the SCHAR higher-order, beam-transport code. Beam macroparticles for this calculation were run through the measured LEBT solenoid B-field. The large beam (≈ 4.5 cm radius), which nearly fills the solenoid bore, is predicted by SCHAR to undergo significant solenoid aberrations. Initial normalized emittance (90% beam fraction) from the ECRIS grows from 0.53 π -mm-mrad to 3.1 π -mm-mrad at RFQ injection. Because the RFQ1 design acceptance is only 2.0 π -mm-mrad, both LEBT emittance growth and mismatch are probably responsible for not reaching the 75-mA RFQ1 limit.

After the RFQ was installed in MPF-18 (a large, high-bay laboratory at Los Alamos), network analyzer measurements were done to baseline the RFQ and to check for shipping damage. The results are as follows:

- Resonance frequency: 267.411 MHz
- Driveline coupling: 2.455
- Reflected power (unloaded Q): 6716.7
- Bandwidth unloaded Q: 6710.9
- Delta phase unloaded Q: 7083.5

These results are within expectations for initial tuning of the RFQ, and indicate the RFQ will be ready for rf power conditioning when the 267-MHz klystrodes come on-line at Los Alamos.

By the end of summer 1993, installation of the CRITS equipment in MPF-18 was well under way. Figure 7.8 shows the CRITS single-solenoid direct injection beamline with the functioning diagnostics. High-power operation of the rf equipment and the RFQ are being delayed until suitable facility ac power modifications are complete. Meanwhile, we have run the injector beam and are proceeding to confirm the good operation seen at Chalk River. The highest current observed at Los Alamos is 78 mA at 50 kV.

A field map of the LEBT solenoid showed dipole and higher-order multipoles, which will produce a

Fig. 7.6 The measured beam profile for the 50-keV, 75-mA hydrogen ion beam used to inject the CRL radio-frequency quadrupole. Reticon TV cameras were used to monitor the light emitted by the beam interaction with the background LEBT gas.

Fig. 7.7. The measured beam profile widths as a function of beam energy for the CRL injector. Both horizontal and vertical profiles are shown.

significant beam deflection. We plan to investigate operation with and without newly designed homogenizer rings for sorting out the higher-order field components.

PDF Injector Project

Several proposed projects will require injector-beam currents higher than can be produced with the CRITS injector. We're designing and building a new high-performance injector, Accelerator Prototype Development Facility (APDF)

injector, based on CRITS and other relevant technologies. Because the injector greatly affects beam emittance and stability, and implements beam turn-on and fault recovery, major injector developments are required for higher voltage, higher current and better-quality beam transport. Most of the new projects will demand at least a 100-mA proton beam accelerated by the RFQ. With typical proton fraction (>75%) in the ECR ion source and the anticipated RFQ transmission (~90%), we will need about

150 mA total extracted beam current from the ion source. The transport electron-equivalent perveance is about 0.4 μPerv for this 75-keV beam energy and indicates the need for careful attention to space-charge effects.

Neutron spallation sources under consideration require high-current, high-duty-factor beams with long-term reliability and stability. Similar requirements apply to the new APDF injector, shown in Fig. 7.9. In our design, we have chosen the CRL ECRIS because it has exceptionally high gas and discharge efficiencies and has already demonstrated impressive lifetimes. We will use a single-gap extraction system based on a proven design used on the FMIT injector. The injector will employ a dc transducer to measure the beam current and CCD cameras to measure the beam profiles. Vacuum pumping will be done with turbomolecular pumps, which afford stable, long-term pumping in the 10⁻⁵ torr range, optimal for beam space-charge neutralization. The low-energy beam transport (LEBT) system will have a dual-solenoid lens system to provide optimal matching to the RFQ accelerator. The tuning diagram for this injector is shown in Fig. 7.10. Provision for automated fault recovery is being incorporated in the control system for this injector.

Initial injector operation will focus on beam characterization using a diagnostic

box at the RFQ match point. Beam-profile measurements will be done at three positions along the beamline to reconstruct the emittance distribution with tomographic methods. Calibration of this emittance measurement will be done with a conventional slit and collector device. This equipment will also determine beam centroids and LEBT alignment errors. A layout showing both the CRITS and APDF is shown in Fig. 7.11.

8X Source Work

Earlier testing with surface-plasma sources (SPS) showed their feasibility for providing high-quality H⁺ beams.

Fig. 7.8. The CRITS single-solenoid LEBT. The beam extracted from the ion source is transported to the RFQ matchpoint.

Fig. 7.9. APDG injector layout.

Fig. 7.10. Alpha-Beta tuning diagram for the dual solenoid LEBT.

However, very high internal power densities precluded the possibility of high-duty-factor operation. We successively tested larger-scale sources (4X and 8X) that showed higher average power capabilities and only slightly lower brightness.

The possibility that an 8X source might run dc and produce H^- beams of interest to the neutral particle beam (NPB) program was first realized four years ago. Since that time, Grumman Corporation performed engineering analyses of proposed cw 8X source designs and Los Alamos National Laboratory built and tested a pulsed 8X source to verify good physics performance. Subsequently, Grumman developed a practical design² and built the cw 8X source.³ A photograph of a completed cw 8X source assembly is shown in Fig. 7.12. In preparation for testing, Los Alamos refurbished the existing high-current test stand and installed the cw 8X source and its special water heating/cooling system. The assembled equipment is shown in Fig. 7.13.

During the past year, we demonstrated that in pulsed operation the cw 8X source gas flow, arc voltage, magnetic field, and discharge current are comparable to the same pulsed 8X source parameters. Based on limited operation, cathode erosion appears consistent with data from the 4X source pulsed operation. The cw 8X source cathode is expected to last at least 50 hours under full-power dc arc conditions.

We have tested the cw 8X source 100-A pulsed arc for pulse lengths up to 31 ms⁴ and have operated the source with up to 9 A of dc discharge current. Arc power may have been limited by thermal desorption of cesium from the anode and aperture cap surfaces. The cesium balance is not quite optimum for high-power dc operation. During these measurements, no visible cesium condensed on the cathode, but visible, undesired layers of cesium formed on the anode and aperture cap surfaces in contact with the source plasma.

Fig. 7.11. Layout of the MPF-18 injector complex.

Fig. 7.12. Layout of the MPF-18 injector complex.

After we modified the source cooling to permit anode and aperture cap temperatures to rise to 340°C and 300°C, respectively, there was greatly reduced cesium buildup on those surfaces in contact with the source plasma. It appears that the source arc will operate at short pulses (≈ 31 ms) with the cathode, anode, and aperture cap surfaces at $\approx 200^\circ\text{C}$. However, we must raise the temperature of the anode and aperture cap to $>300^\circ\text{C}$ to prevent cesium buildup on those electrodes for long pulses (≈ 1 s).

Next year, time and funding permitting, we will continue raising the temperature of the anode and cathode surfaces to obtain long arc pulse and dc operation. There is a potential use of a high-duty-factor, pulsed 8X source on the LANSCE upgrade projects at LAMPF. We hope to demonstrate that the 8X source can meet the duty-factor requirements for these applications.

LDRD Work

Several proposed LANSCE upgrades need high-duty-factor, high-brightness H^- beams. Key issues for these high-power accelerator systems include excellent beam availability, beam chopping, beam-current modulation, initial beam turn-on procedures, and recovery from accelerator faults. Beam chopping is difficult by standard means, such as using the traveling-wave beam chopper now installed in the LEBT at LAMPF. A possible alternative is to chop the beam in the ion source. We found⁵ that a grounded collar, placed near the emission aperture in the 8X source (Fig. 7.14), partially suppresses the e^- and H^- currents extracted from that source. Others find⁶ that biasing the plasma electrode-collar combination in a cusped-field volume source lowers the H^- current extracted from that source. Other problems, such as modulation of the H^- beam current, beam turn-on procedures that do not damage accelerator components, or recovery from injector or accelerator faults, may be mitigated by a fast-biased insert. A beam pulse with ≤ 20 ns rise and fall times is required to minimize beam spill (and component activation) at the

Fig. 7.13. A photograph of the new 8X source mounted on the HCTS, taken from inside the screen room. The water heating/cooling system is on the left, the high-voltage electronic racks and isolation transformer are on the right.

Fig. 7.14. 8X source cylindrical collar geometry. The collar insert (hatched area) is placed in the drift region between the emission aperture and the discharge region. The collar's length is L and its diameter $2R$.

The 0.3-cm inner diameter collar insert is placed adjacent to the emission aperture, just inside the source plasma region. Both electron and ion temperatures are ≈ 1 eV, giving an ion sound speed $v_s = 1.96 \times 10^6$ cm/s. The time estimated to clear the plasma from the 8X source extraction region is $0.15 \text{ cm} / 1.96 \times 10^6 \text{ cm/s} = 26$ ns, close to the required 20 ns. With some modifications (e.g., closely-spaced grids, see Fig. 7.16) desired chopping times lower than 20 ns might be achieved. This equipment, and the electronics to do the proof-of-principle test, are now being installed on the high-current test stand.

Next year, we will attempt to chop the H^+ beam extracted from the 8X source (a Penning surface-plasma source) by applying a bias voltage to the collar insert.

present PSR exit. In a Laboratory Directed Research and Development (LDRD) submission we proposed studying the effect of biasing the 8X source collar insert to determine if the

extracted H^+ beam could be completely shut off.

We obtained funding for this project from the LDRD program, and have designed and built the biased collar (Fig. 7.15a).

Fig. 7.15(a). A schematic drawing of how the biased, cylindrical collar is placed in the 8X source drift region to modulate the extracted H^- beam.

Fig. 7.15(b). A schematic of the electronic signals to be applied to the 8X source discharge and biased collar, along with a possible result of this experiment.

Fig. 7.16. A schematic drawing of how a screen grid will be installed in the 8X source drift region to see if the fall and rise times of the chopped H^- beam can be shortened.

Support on DARHT

The DARHT project successfully completed its milestones in the spring of 1993 with experiments on the integrated test stand (ITS), a 6-MeV prototype section of the 16-MeV induction linac electron accelerator. One of AT-10's staff members contributed to this success by participating in the tickler experiment, a measurement of the gain of transverse motion amplitude vs frequency for a 3-kA, 60-ns beam. He was also responsible for the measurement of beam energy during the 6-ns beam pulse at the 4-MeV injector and after the 2-MeV linac.

Support on the SSC

In an innovative approach to provide personnel support for critical accelerator technology, four of AOT-10's people were temporarily reassigned to the Superconducting Super Collider near Dallas, Texas for several months this past year. These volunteers helped with the final design, fabrication and assembly of several accelerator and beamline components. The hardware assembly process was terminated, prematurely, by the reduction of funds and subsequent project cancellation by Congress.

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Appendix B
Glossary

AP	amplitude and phase
ABC	Accelerator-Based Conversion
ADTT	Accelerator-Driven Transmutation Technologies
AFEL	Advanced Free-Electron Laser
APDF	Accelerator Performance Demonstration Facility
APLE	Average Power Laser Experiment
APS	Advanced Photon Source
APT	Accelerator Production of Tritium
ATW	Accelerator Transmutation of Waste
AXY	A = high-power accelerator, XY = represents the specific application
BCDTL	bridge-coupled drift-tube linac
BEAR	Beam Experiment Aboard a Rocket
BJT	bipolar junction transistor
BPM	beam position monitor
CAD	computer aided design
CAPFAST	commercial schematic editor
CCL	coupled-cavity linac
CDA	conceptual design activity
CEBAF	Continuous Electron Beam Accelerator Facility
CEED	concept enhancement and experiment definition
CRADA	Cooperative Research and Development Agreement
CRITS	Chalk River Injector Test Stand
cw	continuous wave
CWDD	Continuous Wave Deuterium Demonstrator Project
D-Li	deuteron bombarding a lithium target
DARHT	Dual-Axis Radiographic Hydro-Test
DEWPOINT	Directed Energy Weapons Power Integration
DNA	Defense Nuclear Agency
DoD	US Department of Defense
DOE	US Department of Energy
DP	defense programs
DTL	drift-tube linac
ECAD	electronic computer aided design
ECR	electron-cyclotron-resonance
ECRIS	electron-cyclotron resonance ion source
EPICS	Experimental Physics and Industrial Control System
ESNIT	Energy Selective Neutron Irradiation Test
FMIT	fusion materials irradiation facility
FSU	Former Soviet Union
FWHM	full-width-at-half-maximum
GPR	ground penetrating radar
GTA	Ground Test Accelerator
HAM	hybrid amplifier module
HEBT	high-energy beam transport
HFSS	High-Frequency Structure Simulator
HIPERGPR	high-performance ground penetrating radar
HPM	high-power microwave
HPRF	high-power rf
ICN	Integrated Computing Network
IFMIF	International Fusion Materials Irradiation Test Facility

Appendix B • Glossary

IMS	intermediate matching section
IOC	input-output controller
IPE	Institute of Problems of Electrophysics
IQ	in-phase and quadrature
IR	infrared
ITS	integrated test stand
JAERI	Japan Atomic Energy Research Institute
LAMPF	Clinton P. Anderson Meson Physics Facility
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley Laboratory
LDRD	Laboratory Directed Research and Development
LEBT	low-energy beam transport
LINDA	laser induced neutralization diagnostics approach
LLNL	Lawrence Livermore National Laboratory
LLRF	low-level rf
LOG	large-orbit gyrotron
LVDT	Linear Variable Differential Transducer
MDML	Magnet Design and Measurement Laboratory
MRTI	Moscow Radio Technical Institute
NCMS	National Center for Manufacturing Sciences
NCNR	National Center for Neutron Research
NLC	Next Linear Collider
NPB	Neutral Particle Beam
ORNL	Oak Ridge National Laboratory
PFM	pulse-forming network
PIC	particle-in-cell
PID	proportional, integral, and differential
PLC	programmable logic controllers
PSII	Plasma Source Ion Implantation
PSM	phase-step mirror
PSR	Proton Storage Ring
R/S	Rocketdyne/Stanford
rf	radio frequency
RFQ	radio-frequency quadrupole
RKA	relativistic klystron amplifier
RRR	relative resistance ratio
SCL	side-coupled linac
SLC	Stanford Linear Collider
SPS	surface-plasma sources
SSC	Superconducting Super Collider
SST	solid-state triodes
UV	ultraviolet
VFPM	variable-field permanent-magnet
VFQ	variable-field quadrupoles
VLE	vulnerability, lethality, and effects
VME	versa-module European
WEMPE 4	wideband electromagnetic pulse environment
WNR	Weapons Neutron Research