# THE BNL ACCELERATOR TEST FACILITY AND EXPERIMENTAL PROGRAM[1]

Ilan Ben-Zvi

NSLS, Brookhaven National Laboratory, Upton NY 11973
and
Physics Department, SUNY Stony Brook, NY 11794

ABSTRACT

The Accelerator Test Facility (ATF) at BNL is a users' facility for experiments in Accelerator and Beam Physics. The ATF provides high-brightness electron beams and high-power laser pulses synchronized to the electron beam, suitable for studies of new methods of high-gradient acceleration and state-of-the-art Free-Electron-Lasers. The electrons are produced by a laser photocathode rf gun and accelerated to 50 to 100 MeV by two traveling wave accelerator sections. The lasers include a 10 mJ, 10 ps Nd:YAG laser and a 100 mJ, 10 ps $CO_2$ laser. A number of users from National Laboratories, universities and industry take part in experiments at the ATF. The experimental program includes various laser acceleration schemes, Free-Electron Laser experiments and a program on the development of high-brightness electron beams. The ATF's experimental program commenced in early 1991 at an energy of about 4 MeV. The full program, with 50 MeV and the high power laser will begin operation this year.

## THE ACCELERATOR TEST FACILITY

Introduction. The Accelerator Test Facility (ATF) is operated as a user facility for accelerator and beam physicists by the Brookhaven National Laboratory (BNL) for the US Department of Energy. The National Synchrotron Light Source department at BNL has responsibility for the construction, operation, safety and administration of the ATF. The experimental program is coordinated by the BNL Center for Accelerator Physics. Support for the ATF is provided by the Advanced Technology R&D Branch, Division of High-Energy Physics of the DOE. The central theme of the ATF research is the interaction of high-brightness electron beams with electromagnetic energy. For this purpose the ATF is equipped with a laser photocathode rf gun, an electron linac, high-power short-pulse lasers synchronized with the electron beam and a variety of diagnostic equipment. In order to provide a wide range of beam parameters for the users, the electron beam charge may be varied from 0.1 pC at a normalized emittance of $10^{-8}$ m-rad to 1 nC at a normalized emittance of $7 \cdot 10^{-6}$ m-rad. The macropulse repetition rate is variable from 1.5 to 6 pulses per second. The length of a macropulse is 3.5 $\mu$S. In each macropulse one may produce from 1 to 200 micropulses with a FWHM pulse length of 6 ps, at a 12.25 ns period. The electron beam energy from the gun is variable up to 4.6 MeV and the linac energy, initially at 50 MeV, will be upgraded to 100 MeV by providing additional rf power. The Nd:YAG laser radiation at 1.06 $\mu$m with a pulse energy of about 10 mJ and the $CO_2$ radiation at 10.6 $\mu$m with a pulse energy of about 0.1J, both synchronized to the electron beam and each having a pulse length of 10 ps, will be available at the experimental area.

The rf gun. The BNL laser photocathode rf gun is a resonant $\pi$-mode 1½ cell cavity operating at 2856 MHz [1]. The cavity, shown in Fig. 1, is 83.08 mm inner diameter and 78.75 mm long, with a beam aperture of 20 mm. It has a Q of 11900 and

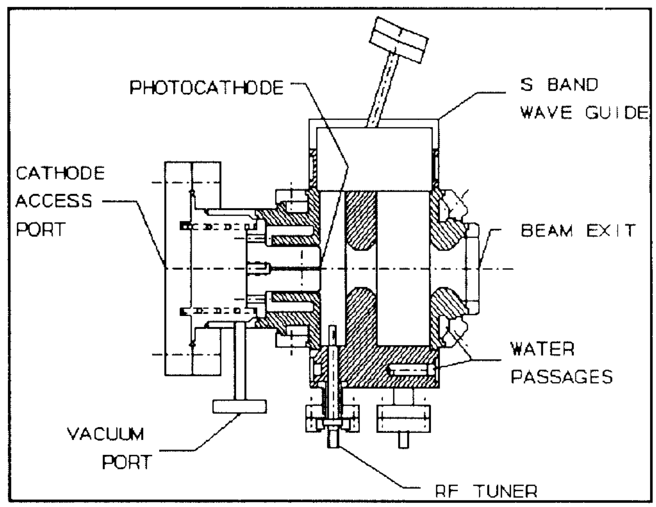


**Figure 1** The BNL Laser/rf Gun.

a calculated shunt impedance of 57 MΩ/m, which corresponds to a beam energy of 4.65 MeV at a structure peak power of 6.1 MW. At this power, the peak surface electric field is 119 MV/m and the cathode field is 100 MV/m. The gun power is derived from the linac klystron using a high-power hybrid junction, and fed through a power attenuator and phase shifter so that the power level and phase can be varied from a few KW up to a maximum of 12.5 MW. For a high-micropulse charge the emittance growth due to space charge effects is minimized by operating the gun in the highest possible electric accelerating field. The rf field contribution to the emittance is minimized in two ways. The first of these involves providing a nearly linear dependence of the transverse fields with beam radius by a suitable cell design. The other uses cancellation of the strong radial fields near the aperture through operation in $\pi$-mode and crossing of the boundary between the two cells when the electric fields vanish. This last condition, in conjunction with the requirement for a high cathode electric field due to the space charge forces, determines the optimal (charge dependent) phase of the laser pulses relative to the rf wave for minimum emittance at the gun output. Since there is no compensation for the transverse deflection at the exit of the gun, the greater part of the rf induced emittance growth takes place there.

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The photocathode. A study of various materials [2] for the photocathode has shown that certain metals have a good combination of quantum efficiency, high damage thresholds, a work function close to the photon energy of the laser and good mechanical and chemical stability. Copper and yttrium metal cathodes proved particularly robust. We are using a frequency quadrupled Nd:YAG laser, with photon energy of 4.65 eV. Yttrium has a work function of about 3.1 eV and a quantum efficiency of up to $10^{-3}$. Thus the photoelectrons can emerge with up to 1.5 eV energy. We may assume that the electrons are emitted with an isotropic angular distribution at the cathode. For a Gaussian laser power distribution with $\sigma_r$=3 mm this would lead to an initial invariant emittance of 3.5$\pi$ mm-mrad. A copper cathode with a work function of 4.3 eV contributes about half the initial emittance but only offers a quantum efficiency of only $10^{-4}$. We have operated both copper and yttrium cathode for prolonged periods in the gun, with vacuum cycling and through power conditioning of the gun, with a negligible loss in the cathode quantum efficiency.

RF gun research. An important aspect of the research at the ATF is the continued development of high-brightness electron guns. In the design of the current version of the ATF gun, the beam dynamics in the gun has been calculated with a version of PARMELA, modified to include ejection of low-energy electrons from a photocathode by a laser pulse as well as the image charge effects at the cathode [1]. The rf fields were calculated by SUPERFISH and transferred to PARMELA as Fourier coefficients. The rms invariant emittance $\epsilon_n$ has been optimized for a charge of 1 nC at a cathode field of 100 MV/m. In this simulation the laser pulse length is $\sigma_z$=0.6 mm and its spot radius is $\sigma_r$=3 mm. The optimal $\epsilon_n$ is 7.3 $\pi$ mm-mrad, which is mostly due to space charge effects (6.2 $\pi$ mm-mrad), while the cathode and the rf field contribute the remaining emittance. The energy spread is $\sigma_E$=17 keV. This small value is the result of the short laser pulse and is not due to an energy selection slit. In recent work [3] time dependent correlations were found between the transverse displacement and the divergence of the electrons exiting the gun. In calculating the emittance for slices which are one tenth of the bunch length, a value which is five times smaller has been found. This suggests that an emittance correction method may be found to result in much improved emittances. A collaboration between BNL and Grumman Aerospace Corporation has been set up to develop the next generation photocathode gun for the ATF. The MAGIC particle-in-cell (PIC) code is being used for this research. This code is also being applied to the present gun for confirmation of the modeling. This code calculates the rf fields of the cavity internally and provides for a complete and accurate description of wake fields and space charge forces. The MAGIC code simulation [4] includes the fields in the exit region of the gun. The resolution of the MAGIC simulations was increased beyond that previously available in order to properly resolve the bunch and suppress grid heating [5]. The increased resolution, coupled with a field algorithm which damps artificial particle noise, results in emittance values significantly lower (up to a factor of 2 lower) than those predicted by our PARMELA simulations. The results which are forthcoming from the ATF experimental program should resolve the discrepancy.

Low-energy beam transport. The ATF low-energy beam transport, shown in Fig. 2, is designed for easy illumination of the cathode by the laser, longitudinal and transverse phase space diagnostics, bunch

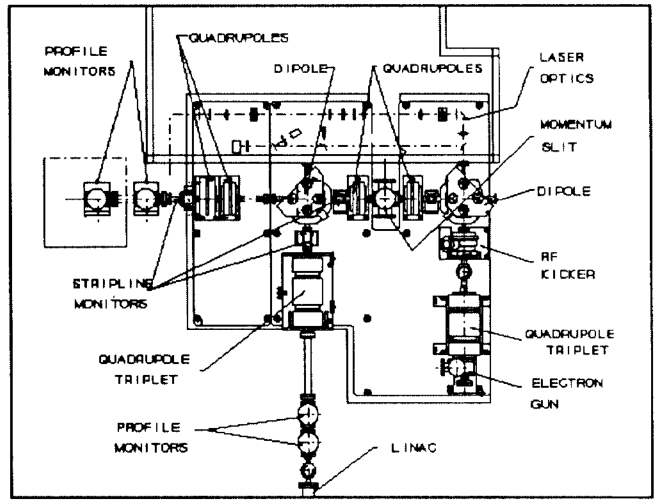


**Figure 2** The ATF Front End

compression and availability of the beam for experiments at low-energy. The LEBT consists of two quadrupole triplets and a 180° achromatic double bend. It is equipped with a momentum selection slit at the maximum horizontal dispersion point (4 mm per %), a vertical rf deflection cavity for streak measurements, phosphorous screen beam profile monitors with CCD cameras, fast strip line wall current monitors and Faraday cups. The momentum selection slit has a remote control, beam charge measurement capability and a phosphorous layer monitored by a CCD camera. The rf deflection cavity makes it possible to measure the longitudinal phase space of the 6 ps electron bunches. The laser optics of the front end provides a remote control of the UV light spot on the cathode: intensity, position and size. The laser power is monitored by an energy meter and a fast photodiode and the spot shape and size by a CCD camera. The LEBT has been modeled with a version of TRANSPORT with linear space charge added to study the effect of this on the beam profiles [6]. The first triplet is operated in an asymmetric mode to compensate for certain high order aberrations. For the 1 nC beam described above, the beam pipe scrapes about 25% of the beam at the center of the first quadrupole triplet. The geometric horizontal emittance $\sigma$ growths from 0.8 $\pi$ mm-mrad to about 2.2 $\pi$ mm-mrad and the vertical emittance is preserved in passing through the transport line. The horizontal emittance growth is due to the large divergence which is predicted by PARMELA at the exit of the gun, $\sigma_{x'}$=28 mrad. This calculation is for an optimized gun at 1 nC. Thus the conditions for an optimal emittance at the gun are not optimal when the LEBT is considered as well. A reduction in the laser beam spot on the cathode from $\sigma_r$=3 mm to about 2 mm would result in a negligible increase in the gun emittance but would reduce considerably the emittance growth in the LEBT.

The linac. The ATF linac consists of two SLAC linac sections, (2$\pi$/3 mode, disc loaded, travelling wave, 3.05 meters long) produced at IHEP Academia Sinica. The linac and gun are driven by a single XK5 klystron delivering about 25 MW of peak power at a frequency of 2856 MHz and with a pulse duration of 3.5 $\mu$s. The rf system is designed to run at repetition rates up to 6 Hz so average power and heating are minimal. A phase locked oscillator operating at the 35th harmonic of 81.6 MHz is used to drive a series of solid state and triode amplifier stages to obtain the up to 1 KW of drive power for the klystron. The fundamental also drives and synchronizes the Nd:YAG laser. The linac and waveguide system are temperature stabilized to within ±0.1°C. The gun has an independent regulation system. Calculations of the linac beam dynamics have been done numerically, including the effects of space charge and wake fields. We find that for a properly matched transverse beam no increase in transverse emittance occurs in the acceleration process through the linac. An increase of the longitudinal emittance takes place for a 1 nC, 6 ps beam microbunch due to the combined effect of the short-range longitudinal wake field and the curvature of the accelerating waveform. The effect is minimized in the usual way by a proper choice of the bunch phase. A second modulator and klystron are proposed for future operation of the ATF, so that the gun and the linac will be driven by two independent rf amplifiers. This will improve the amplitude and phase control and increase the ATF energy to about 70 MeV. Upgrade to 100 MeV can be achieved by providing a klystron for each accelerator section.

Adaptive control. While the macropulse-to-macropulse energy of the linac is very stable, various effects contribute to the energy spread of the beam within a single macropulse, which will contain up to 200 microbunches. Beam loading effects would produce an energy variation of about 8% during the macropulse. The modulator voltage ripple of ±0.3% contributes ±0.6% to the rf power and an estimated ±2° to the phase error with the klystron saturated. Our approach to this problem is described in another contribution to these proceedings [7]. An attenuator and phase shifter in the low level drive system vary the amplitude and phase of the klystron unsaturated output. These control elements are driven by arbitrary function generators (AFGs). A PC computer reads a digitizer which samples the cavity field and phase values and sends data to the AFGs. RF amplitude stability of better than ± 0.2% by computer control and phase stability of ±0.6° by manual control were obtained over a 3 µs pulse. The two klystron systems will use independent control systems for the gun and linac.

Beam line diagnostics. Part of the ATF high-energy beam transport line and its diagnostic system are shown in Fig. 3. ATF electron beam diagnostics incorporate non-destructive, strip-line beam position monitors with a wide band response, to allow for micropulse-by-micropulse measurements of the beam position (or energy) and current. Faraday cups are provided at a few locations for exact beam current measurements. Remotely controlled destructive beam profile monitors based on phosphor screens and CCD cameras are used for emittance measurements [8]. A large number of pneumatically operated monitors will give beam position and size information. Momentum analyses at both 4.5 MeV and 50 MeV are made by measuring the beam profile (using a phosphor screen) and position (using a strip line detector) at the maximum dispersion points. Beam profile measurement of the 50 MeV beam in the time domain will be done by means of a fast magnetic septum kicker system and the phosphor screen - CCD camera monitor. An emittance selection system is incorporated in the post-linac beam transport line, comprising two collimators with a variable aperture. The collimators are phosphor coated and monitored by a CCD camera. The emittance selection system is designed to define the extremely small emittance beams of the laser acceleration experiments [9]. A fast beam profile detector is being developed [10], based on secondary emission from a meander strip line. This detector is designed to convert the beam intensity distribution in a given dimension to a pulse height distribution in time for each microbunch (12.25 ns period). A silicon semiconductor detector comprising microstrips 1 µm wide will provide an ultra-high-resolution beam position monitor for positioning the extremely small beams used by the laser acceleration experiments.

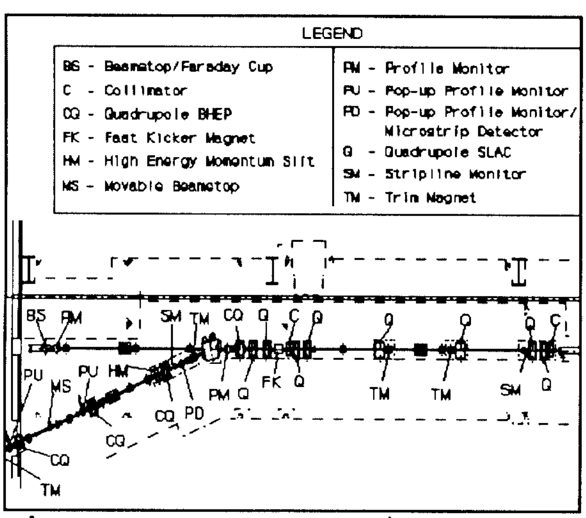


**Figure 3** The ATF High Energy Beam Transport Line

Laser systems. A Nd:YAG laser system is used for exciting the gun photocathode and controlling a semiconductor switch in the picosecond $CO_2$ laser. This system includes a Spectra-Physics CW oscillator (wavelength 1064 nm), mode locked to the 40.8 MHz, a sub-harmonic of the 81.6 MHz rf reference source. A Lightwave Electronics series 1000 timing stabilizer [11] is used to phase-lock the oscillator to the reference, reducing pulse-to-pulse timing jitter, or phase noise, of the laser to better than 1 ps. The oscillator pulse (about 80 ps long) is then chirped in a 200 m optical fiber and amplified in a pulsed regenerative amplifier. [12] The amplifier bandwidth chops the chirped pulse to about 10 ps. The output is frequency doubled and then transported about 30 m to the gun hutch where a second doubling takes place. At this point there is an energy of 100 µJ in a 6 ps pulse at the operating wavelength of 266 nm. This is sufficient to produce 1 nC of electron charge from a copper photocathode. A modification of the Nd:YAG system will provide a pulse train mode, in which up to 200 microbunches, separated by 12.25 ns may be switched by a Pockels cell. Part of the output from the Nd:YAG at 1064 nm is used to slice a short, synchronized $CO_2$ laser pulse of 10 psec duration out of a 100 ns pulse from a $CO_2$ oscillator by using germanium plates which change from transmitters to reflectors when hit by 1064 nm light [13]. A broadband, 4 Atmosphere isotopic mix $CO_2$ amplifier, is being developed. The amplifier, which has a 2 m long active area and a UV pre-ionized TE discharge, has been developed in collaboration with Los Alamos National Laboratory. We expect the amplifier to boost the pulse energy from 10µJ to over one hundred mJ. The isotope mix is $^{12}C^{16}O_2/^{12}C^{18}O_2/^{12}C^{16}O^{18}O$ at ratios of 1/1/2 in a closed loop longitudinal gas circulation. A warm (100°C) catalytic converter is used. Since the timing of the $CO_2$ pulse is determined by the Nd:YAG pulse, it is synchronized to the electron beam as well.

Control system. The control system is based on a VAX 4000 series system. A Microvax-II/GPX is used off-line for software development and testing. Control and monitoring of the facility's devices (magnet power supplies, beam position monitors, timing system, etc.) is through a Kinetic Systems Corporation CAMAC byte-serial highway driver connected to 4

CAMAC crates. From the CAMAC, communication to local devices is via industry-standard hardware interfaces and protocols such as EIA-RS-232 and IEEE-488. Both machines are equipped with Ethernet interfaces and are connected by DECnet to HEPNET and Internet. The computers operate under version 5.4 of DEC's VMS operating system. Support for software development in both C and FORTRAN programming languages is provided. In addition, a commercial control system software package, marketed by Vista Control Systems, Inc., is used to build window-based operator interfaces. All windowing operations are done using DECwindows, Digital's implementation of the X-windows standard. Operators interact with the control system through "point and click" pull-down menus which graphically display controls, overviews of the facility's status and alarm conditions. By employing X-windows technology, these detailed graphic presentations will be available throughout the ATF. The Vista package also includes a database generator, various report writers, a line sequencer and a library of program development routines.

## THE EXPERIMENTAL PROGRAM

General. One experimental beam line at the gun energy is available as a branch of the LEBT and three high-energy beam lines are available at the experimental hall, shown in Fig. 4. The high-energy beam lines are

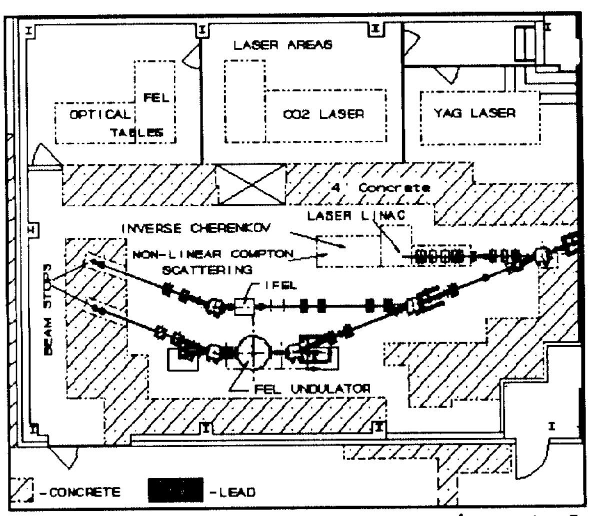


**Figure 4 The ATF Experimental Hall and Laser Systems**

equipped with emittance selection as well as diagnostics for the longitudinal and transverse emittance, beam profile, energy, beam position and current. The $CO_2$ laser radiation may intercept two of the lines in order to perform experiments on laser acceleration or photon-electron scattering. The third line is dedicated to FEL experiments. Proposals for experiments or letters of intent are considered for approval by the Steering Committee of the BNL Center for Accelerator Physics. The currently approved experiments at the ATF are:

Visible FEL (BNL, Stony Brook, Rocketdyne)
Grating Acceleration (BNL, LANL, Princeton, UCLA).
Nonlinear-Compton Scattering (Princeton, BNL, LANL).
Inverse Cerenkov Acceleration (STI, BNL, LANL).
Study of Spiking Phenomena in FELs (Columbia).
Room temperature, pulsed Microwiggler (MIT).

In additions, the CAP committee has received the following proposals and letters of intent:

Inverse FEL (BNL, LANL, Yale, UCLA).
Fast-Excitation Wiggler Development (BNL)
Cerenkov and Metal Grating FELs (Dartmouth).
Cyclotron Resonance Accelerator (MIT)
Superconducting Cavity Wakefield Studies (Cornell)
FEL and Electron Beam Optics and Diagnostics (Rocketdyne).

A user's meeting and simultaneous CAP committee meeting are scheduled for October 1991 at BNL. In the following we shall describe briefly the experiments which are currently approved for the ATF.

Visible FEL. (Spokesperson I. Ben-Zvi, BNL and SUNY Stony Brook). This FEL oscillator experiment [14] is designed to explore the short wavelength limit imposed by emittance in compact accelerators. A novel superferric microundulator [15] with a period of 8.8 mm, gap of 4.4 mm and axial magnetic field of 4.7 kG will produce radiation at a wavelength of 500 nm with the 50 MeV ATF beam. This FEL will be used as a test-bed for the Columbia and MIT experiments. The FEL interaction and resonator design were studied in detail [16]. An output power of 10 MW peak and a gain of about 25% are expected at the ATF beam parameters but with only 50 A peak current.

Grating Accelerator. (Spokesperson R.C. Fernow, BNL). This experiment is designed to investigate new methods of particle acceleration using a short-pulse $CO_2$ laser as the power source and grating-like structures as accelerator 'cavities' [17]. The $CO_2$ laser will be focussed to a 3 mm long line on the surface of the microstructure. With 10 mJ of laser energy in a 10 ps pulse, the electric field in the spot will be around 1 GV/m. Various accelerating microstructures are being developed [18] as well the techniques to guide and diagnose micron sized beams in structures of the same scale. The structures and diagnostics rely on advanced silicon microfabrication techniques which are being explored at BNL.

Nonlinear Compton Scattering. (Spokesperson K.T. McDonald, Princeton U.). This investigation of the nonlinear Compton scattering is the first experiment in a program to study the nonlinear quantum electrodynamics of electrons and photons in an intense electromagnetic wave [19]. The 10 $\mu m$ $CO_2$ laser beam with a peak intensity of $>10^{15}$ Watts/cm$^2$ will be brought into a head-on collision with a single bunch of 50 MeV electrons at the ATF. At such intensities it is probable that an electron absorbs several laser photons before emitting a single photon of higher energy. In addition, the transverse oscillations of an electron inside the laser beam are relativistic. This leads to a shift in the effective mass of the electron that is discernible in the spectrum of radiated photons.

Inverse Cerenkov Acceleration. (Spokesperson W.D. Kimura, STI Optronics). The goal of this program is to build upon earlier Stanford experiments [20] and demonstrate Inverse Cerenkov Acceleration (ICA), using radially polarized laser beam and axicon focussing [21]. Preliminary scaling and modeling have shown the viability of this method for electron acceleration to high energies [22]. A computer modeling for the ATF design parameters (50 MeV beam, 10 GW peak $CO_2$ laser power etc.) was performed. A radially polarized laser beam in a medium of low-pressure hydrogen gas was assumed. The result was an acceleration of over 25 MeV in a 20 cm interaction length [23].

Study of Spiking Phenomena in FELs. (Spokesperson T.C. Marshall, Columbia Univ.) In this research project, spiking phenomena (very short pulses of high-power radiation) will be investigated. Spiking has been observed at Columbia [24] in mm wavelength and at Stanford [25] in the infra-red. At the ATF spiking will be explored in the visible range. The spike is an energy-compression feature that extracts energy from a group of electrons in the slippage distance and concentrates it into a shorter interval [26]. The short spikes of high-power radiation may have useful applications. Alternately the spiking can be eliminated by careful adjustment of the resonator detuning.

Pulsed Electromagnet Microwiggler - Driven FEL. (Spokesperson G. Bekefi, MIT). In this research program an FEL experiment will be carried out on the ATF using a 70 period, 8.8 mm/period pulsed electromagnet wiggler with 4.4 mm gap [27]. This wiggler has a planar geometry and separately tunable half periods. A 20 period sub-section of this wiggler has been tested recently [28]. The measured peak axial magnetic field was 4.2 kG at a current (per coil) of 48 amperes. The field uniformity without tuning is 1% rms. The MIT study of this class of microwiggler has demonstrated 0.4% rms random field error and repetition rates of 1 to 2 Hz with 1 ms half sine waves. This performance is obtained using a very simple technology (water cooling and Microsil ferromagnetic cores).

Operational Status. All of the electron gun and linac systems have been installed and operated at or close to design levels. The gun has been operated at incident power levels over 6 MW and has reached a cathode surface electric field of 98 MV/m. The measured shunt impedance is 50 MΩ/m. The Nd:YAG laser has been operated for extended periods. The UV beam (265 nm) on the gun cathode has reached pulse energies of 180 $\mu$J, well above the design value. Photo-ejected electrons were accelerated to 4.2 MeV and the charge and emittance were measured at various energies. The laser pulse width was derived by measuring the energy spread at the low-energy beam transport center. This procedure results in a FWHM laser pulse width of 5 ps and a centroid jitter of 0.8 ps rms over a period of 10 minutes. With a measured charge is about 1.0 nC, this results in a peak photoemitted current of 150 Amps. There is yet an uncertainty concerning the value of the electron pulse length. A streak camera measurement of the electron pulse length will be done shortly. The measured normalized rms emittance is 4.0 $\pi$ mm-mrad at a charge of 1.0 nC. A quantum efficiency for the copper cathode was measured to be about 7 x $10^{-5}$. All of the ATF transport elements are in place and are operational from the central control computer. The magnetic field quality of all of the transport quadrupoles has been measured using a rotating coil and spectrum analyzer to establish the multipole content, magnetic center and excitation curve. The beam optical elements have been surveyed with a tolerance of ±0.1 mm. The $CO_2$ laser oscillator and amplifier systems have been delivered from Los Alamos. The germanium optical switches have been operated and a short $CO_2$ pulse has been generated. The user program has started with a measurement of Smith-Purcell radiation at the LEBT beam line. The shielding of the gun, linac and experimental hall is done and the shielding of the high-energy beam transport in progress. The beam dump shielding will be constructed following the installation of the experimental hall beam transport elements which is being done at the present time.

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