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TITLE: **COMPACT FREE-ELECTRON LASER AT THE LOS ALAMOS NATIONAL LABORATORY**

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Compact Free-Electron Laser at the Los Alamos National Laboratory*

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ABSTRACT

The design and construction of a second-generation free-electron laser (FEL) system at Los Alamos will be described. Comprising state-of-the art components, this FEL system will be sufficiently compact, robust, and user-friendly for application in industry, medicine, and research.

1. INTRODUCTION

We initiated the Advanced Free-Electron Laser (AFEL) project at the Los Alamos National Laboratory to build a second-generation free-electron-laser (FEL) system. Our goal is to demonstrate that an FEL that is suitable for industrial, medical, and research applications can be built. State-of-the-art components will be incorporated so that the FEL system will be compact in size, robust, and user friendly. The system will later be used to research and develop advanced FEL components, such as electron sources, wiggler-magnet arrays, optical systems, diagnostics, and control systems.

In the initial FEL system, a 20-MeV high-brightness beam will be injected into a 15-period conventional wiggler to produce nominal 3.7-μm light. We will incorporate such state-of-the-art components as a laser-driven photoelectron source, a compact high-gradient accelerator, a computer-based control system, and permanent-magnet beam-transport elements into the system. These subsystems and our planned future upgrades are described in this paper.

2. FACILITY

Figure 1 shows a layout of the facility[1]. The total floor area is 40 ft by 70 ft. The FEL system will be installed in a radiation vault that is 12 ft by 25 ft. The vault has 4-ft-thick concrete wall and a 6-in-thick steel ceiling to provide radiation shielding. A control room and a room housing a drive laser for the photoelectron source and the diagnostics of the FEL light are located at adjacent sides of the vault.

Figure 2 depicts the layout of the FEL system. The electron beam is generated by a high-brightness accelerator and delivered to a 6 ft by 10 ft optical table. The optical table, which is mounted vertically, supports the beamline and the wiggler. After traversing the wiggler, the beam is transported to a beam dump that is below ground level.

3. HIGH-BRIGHTNESS ACCELERATOR

The high-brightness accelerator comprises a laser-driven photoelectron source[2] and a high-gradient accelerator. It is designed to produce an electron beam with an instantaneous transverse emittance that is > 10π mm mrad and an energy spread of < 0.1%. Other beam parameters are listed in Table 1.

The photocathode, formed from CsK_2Sb, has a diameter of 10 mm. Figure 3 is a schematic of the drive laser[3], which comprises an Nd:YLF mode-locked laser, a fiber-optic pulse compressor, and Nd:YLF amplifiers. The drive-laser beam has a wavelength of 523 nm. The 10-ps micropulses are emitted at a rate of 108 MHz; the 10-μs macropulses are emitted at a rate of 10 Hz. At an macropulse-averaged power of 1 kW, the drive laser can produce the required micropulse charge of 4.6 nC as long as the photocathode maintains a quantum efficiency of > 0.2%.

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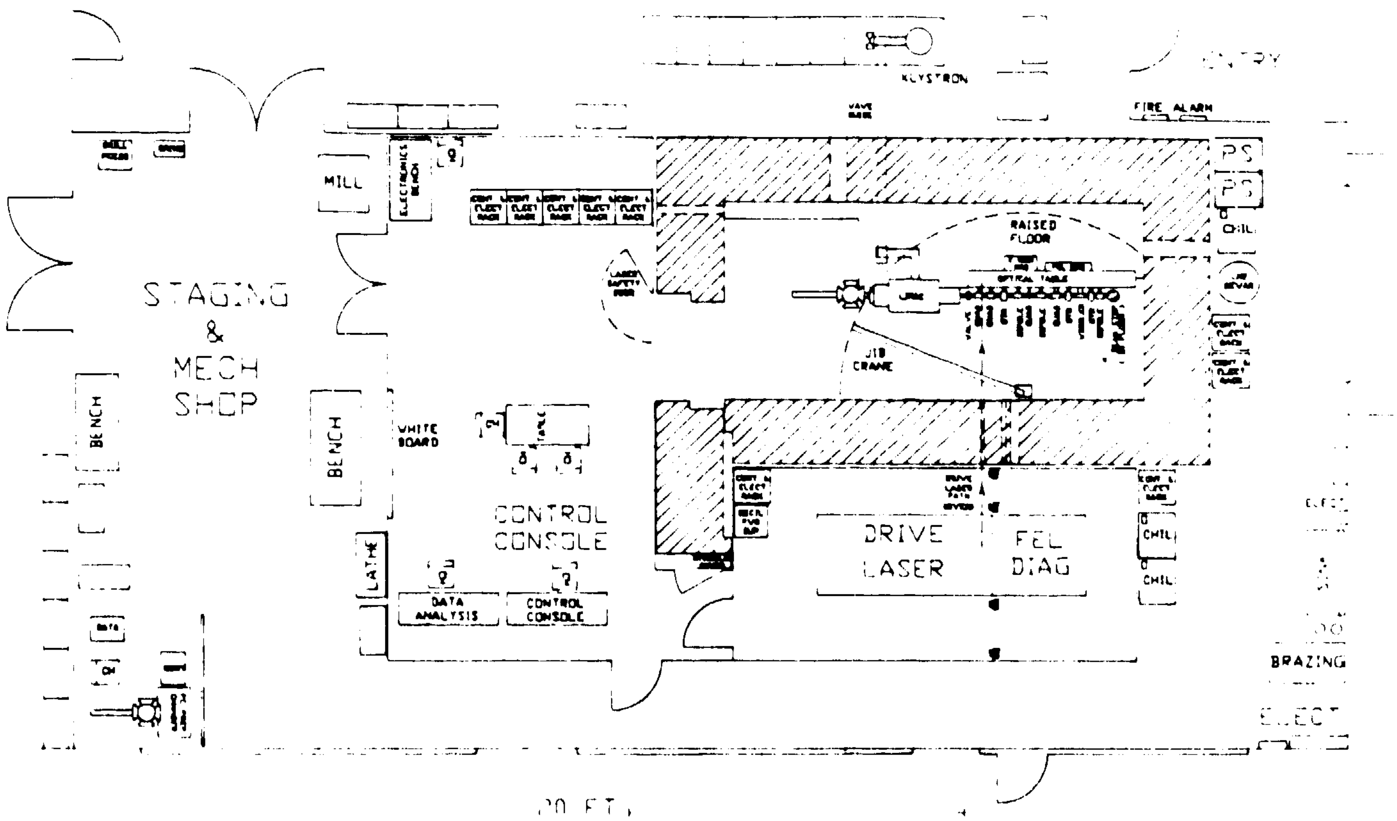

Fig. 1. Layout of AFEL Facility.

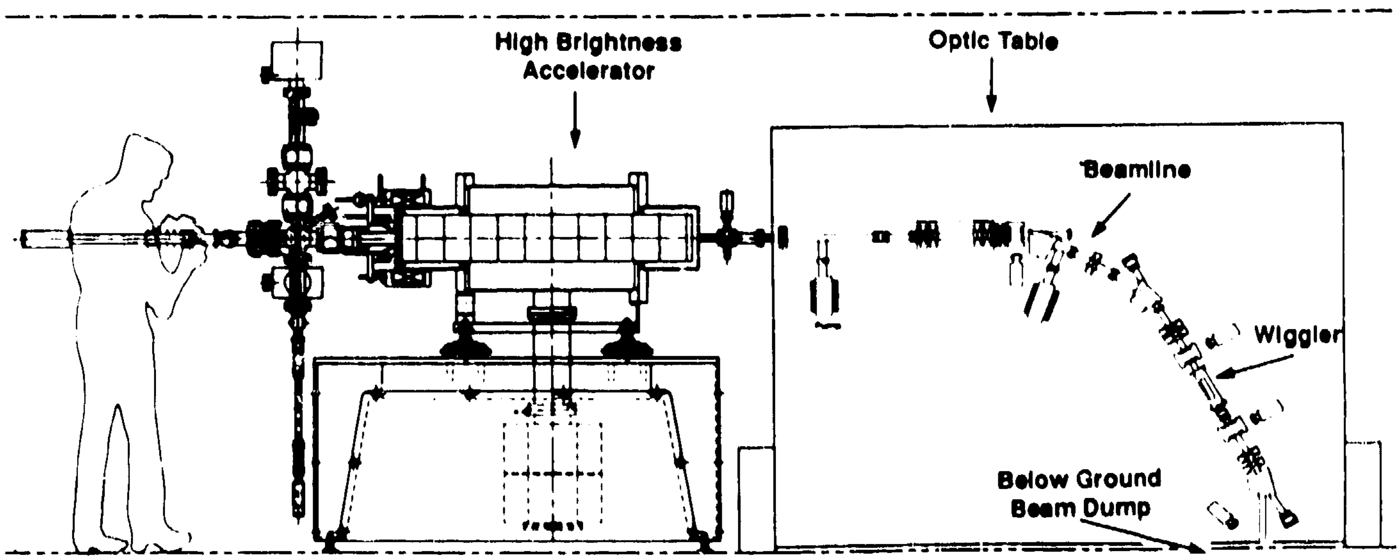

Fig. 2. Layout of the FEL system.

Table 1
AFEL beam parameters

charge per micropulse	2.6 (4.6)[a]	nC
shape of micropulse	gaussian (square)	
micropulse length	11.7 (15.4)	ps
peak micropulse current	220 (310)	A
micropulse frequency	108	MHz
average macropulse current	0.28 (0.50)	A
output energy	20.1	MeV
macropulse length	10 (50)	µs
macropulse rate	10 (20)	Hz
macropulse beam power	5.6 (10.0)	MW
instantaneous energy spread	< 0.1	%
instantaneous emittance	< 10	π mm mrad
micropulse energy spread	< 0.3	%
micropulse emittance	32 (20)	π mm mrad
duty factor	10^{-4} (10^{-3})	

[a] All numbers in brackets are parameters for accelerator operation at liquid-nitrogen temperature.

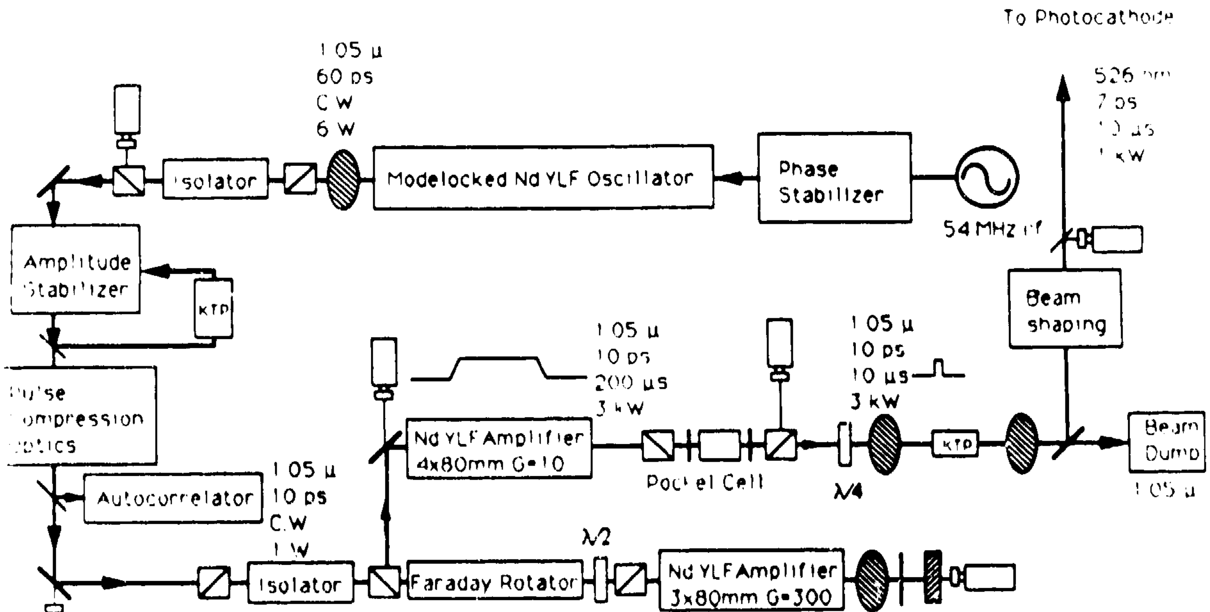

Fig. 3. Schematic of the drive laser.

Figure 4 is a schematic of the high-gradient accelerator, consisting of a vacuum vessel and an on-axis-coupled structure that operates at the π/2 mode. It has 10 full accelerating cells and one half accelerating cell. Initially, the structure will be operated at a temperature of 90°F to produce a 20-MeV beam with an average macropulse current of 280 mA. At a later stage, the structure will be operated at liquid-nitrogen temperature. At this lower temperature, the reduced power loss at the structure will allow a higher average macropulse current of 500 mA. Six titanium rods support the the structure inside the vacuum vessel. These rods provide the thermal insulation necessary so that we can operate the structure at liquid-nitrogen temperature. The arrangement of these rods are designed so that their thermal expansion will produce only a rotation of the structure with no transverse displacements.

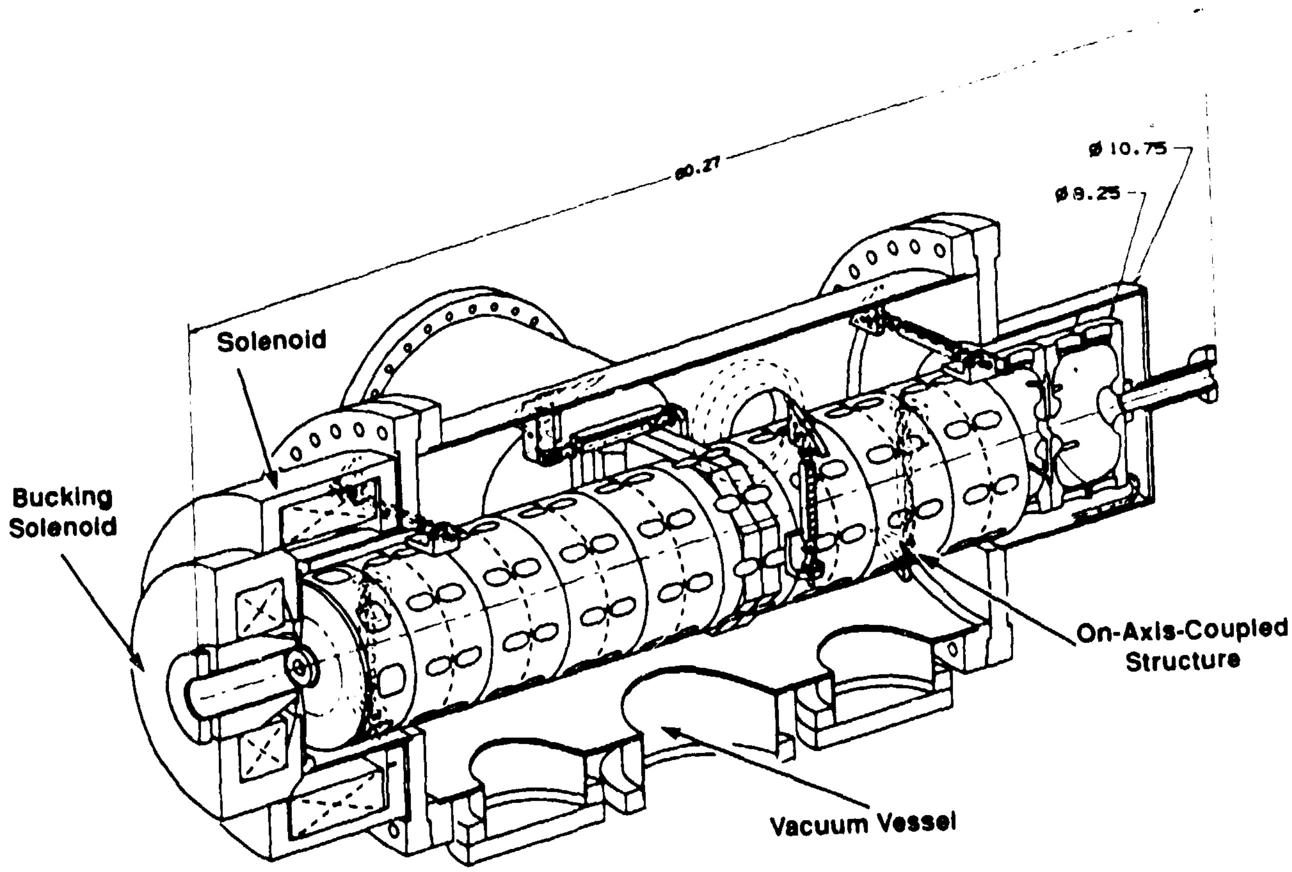

Fig. 4. Schematic of the high-gradient accelerator. Dimensions are in inches.

The photocathode-emitted electron beam is focused by a 1-kG axial magnetic field that is provided by a solenoid outside the vacuum vessel and extends over the first two accelerating cells. To obtain optimum emittance, magnetic field is reduced to zero by a bucking solenoid at the cathode (Fig.4).

We have designed the structure as follows to produce high-quality electron beams[4]. First, we will use a four-slot coupling scheme at the first two accelerating cells (Fig. 5) to eliminate the quadrupole forces that are produced by a conventional two-slot coupling scheme. In a region with a solenoidal field, a quadrupole force causes emittance degradation of the beam. Second, we will use a two-slot coupling scheme for the rest of the structure to minimize the probability of regenerative beam breakup. With the coupling-slot orientation rotated by 90° between neighboring accelerating cells, the couplings of dipole modes are greatly reduced compared to the case of four coupling slots. Third, we will accelerate the electron beam in a high field gradient, 25.4 MV/m at the first half cell and 21.5 MV/m at the rest of the accelerator, to minimize the emittance growth caused by space-charge forces. Fourth, we will tune the first coupling cell to a 5 MV/m field level so that multipactoring can be avoided at a solenoidal field of 1 kG.

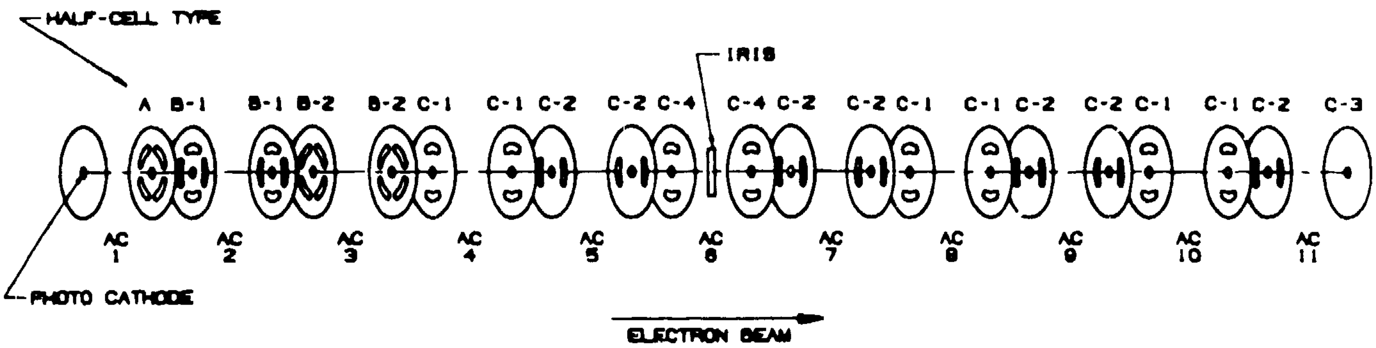

Fig. 5. Cavity-coupling scheme of the high-gradient accelerator structure. The orientation of the coupling slots are shown. AC's are the accelerating cells.

4. BEAMLINE

Figure 6 is a schematic of the beamline[5]. We use two quadrupole doublets to match the beam emerging from the accelerator to the rest of the beamline. The use of a matching section reduces the interdependence of beam dynamics between the accelerator and the rest of the beamline, and thus simplifies the setup and operation of the FEL system. The rest of the beamline consists of a 60° achromatic bend, a wiggler, a spectrometer, and a below-ground beam dump. To minimize the FEL system's size, we design very compact components.

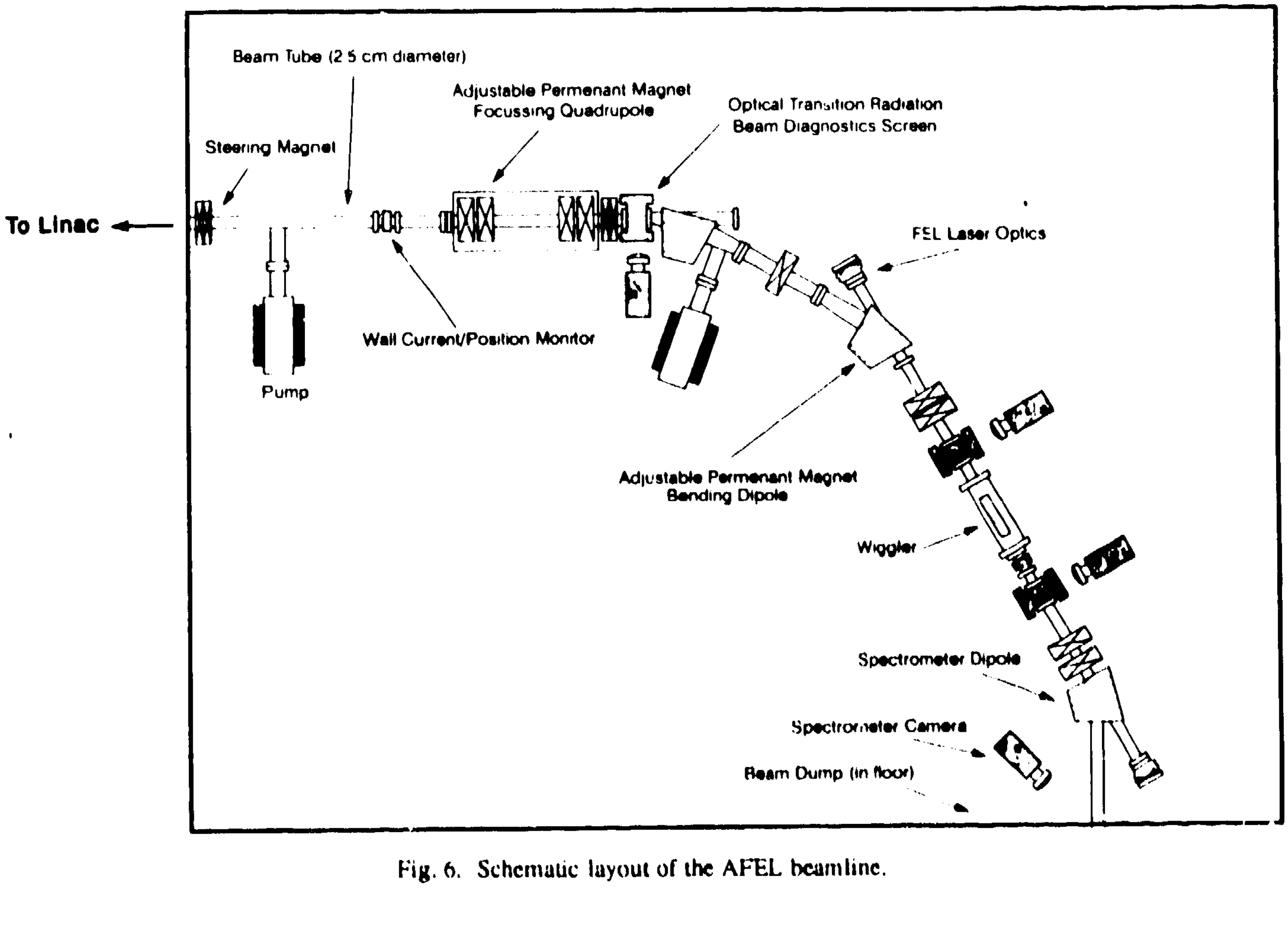

Fig. 6. Schematic layout of the AFEL beamline.

We use permanent-magnet quadrupoles and dipoles because of their compact size, simple design, robustness, and lesser demands on power and water cooling. Figure 7 and 8 show the design of the quadrupole and the dipole[6]. we can vary the magnetic fields by using stepper motors. The operating range of the quadrupole is between -10 and +60 T/m, and that of the dipole is between 0.1 and 0.5 T. Both the quadrupole and the dipole show good linearity over their respective operating ranges.

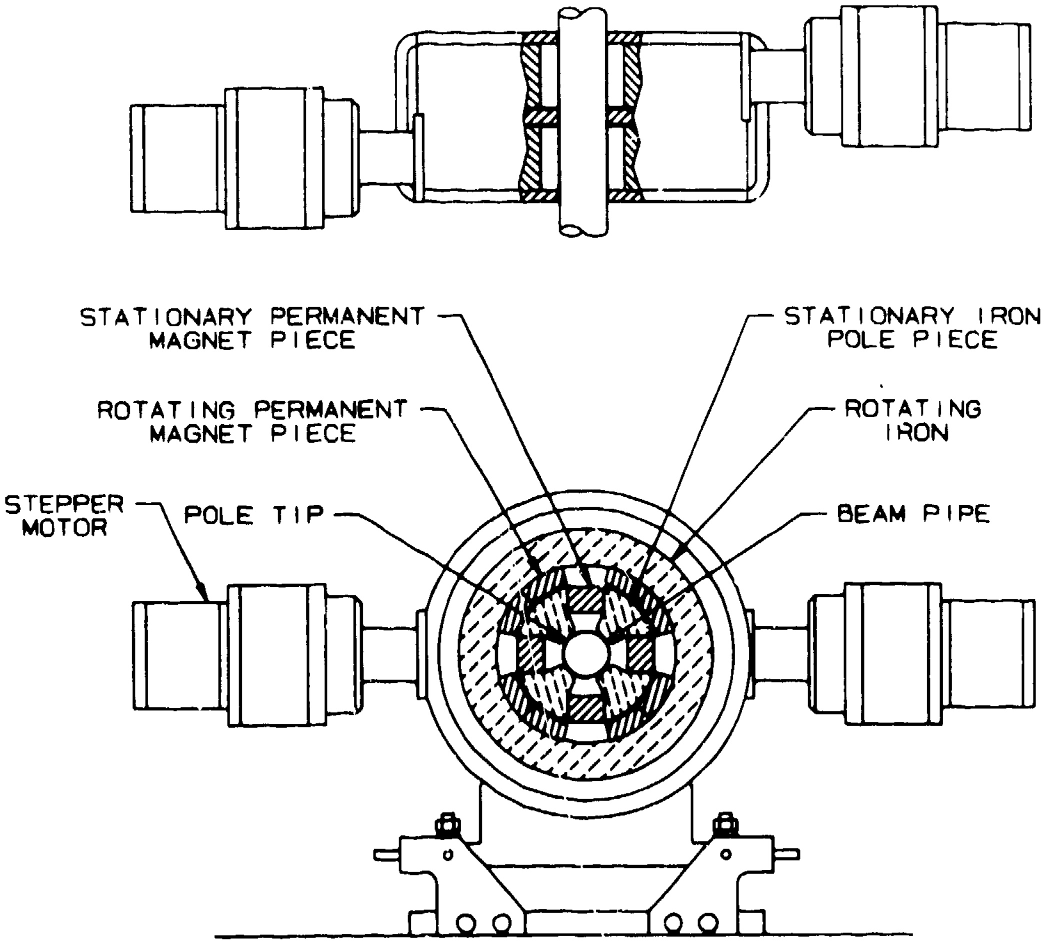

Fig. 7. AFEL quadrupole doublet design.

We design the beamline to minimize emittance growth caused by wakefields. We use only 1-in beampipe throughout the line. At the achromatic bend, we keep the beam size small to obtain a large beam divergence. The beam can therefore tolerate large wakefield effects without significantly increasing the emittance. For a beam that remains on axis in the bend, we estimate that the emittance growth caused by the wakefields generated by the adjoining pipes for the drive-laser and FEL beams will be 0.33%. Additional emittance growth is expected when the beam is off axis (Fig. 9).

5. BEAM DIAGNOSTICS

We have located diagnostic equipment along the beamline to monitor various beam parameters. Table 2 is a list of diagnostic devices that we use and the parameters that we monitor.

We will use beam position monitors which have four short capacitive pickups[7]. They have a position accuracy of 25 μm. Beam position monitors interlaced with Lambertson coils that are manufactured on printed-circuit boards direct the electron on axis.

We monitor the beam emittance by observing optical transition radiation[8] (OTR). OTR is produced when the electron beam impinges on a metallic surface.

Table 2
Diagnostic devices used in the AFEL system

"button" beam position monitor	beam position macropulse current
resistive wall-current monitor	micropulse current
OTR diagnostic	transverse emittance beam size beam divergence
spectrometer	beam energy

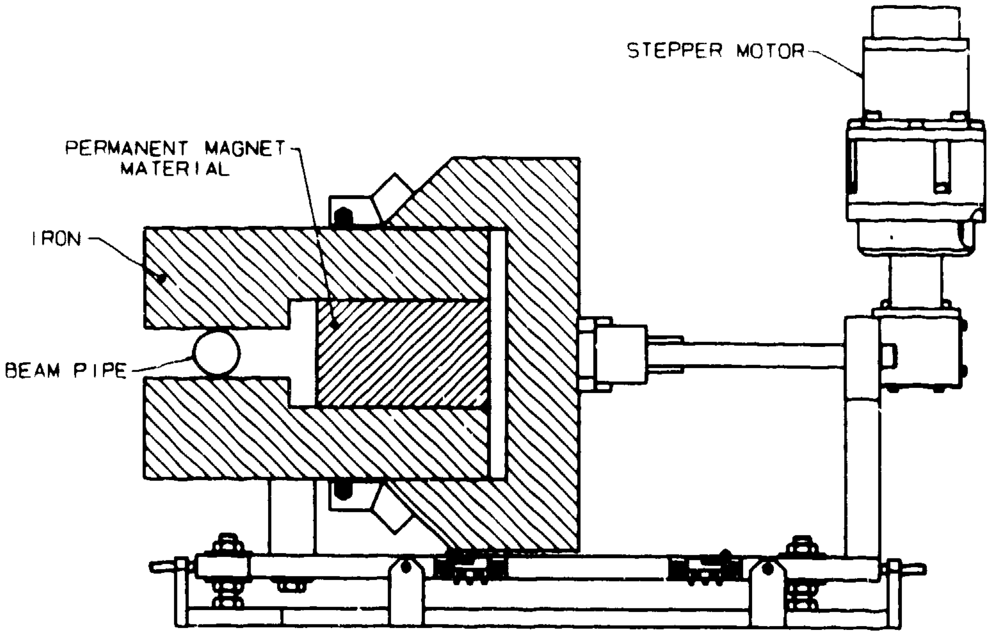

Fig. 8. AFEL dipole design.

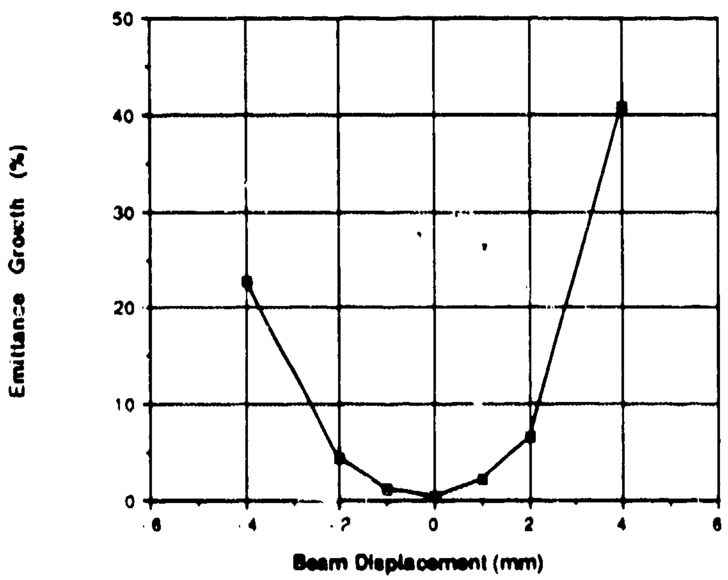

Fig. 9. Emittance growth at the achromatic bend as a function of beam displacement off axis.

6. CONTROL SYSTEM

The entire facility is engineered to interface with a computer-based control system[9] to minimize staffing requirements and to make the system more user friendly. We will use the computer initially to monitor the system and later to perform closed-loop controls. The control system is the second generation of a control system developed previously for the Ground-Test Accelerator in Los Alamos.

Figure 10 shows a schematic of the AFEL Control System hardware. The control console, a SUN/Sparc Workstation, is connected to a VME crate through an EtherNet. The following controllers are included in the VME crate: a GBIP (IEEE-488) controller which connects with most commercial instruments; an Allen-Bradley crate which performs all low-speed digital and analog I/O; and other controllers such as the stepper motor controllers.

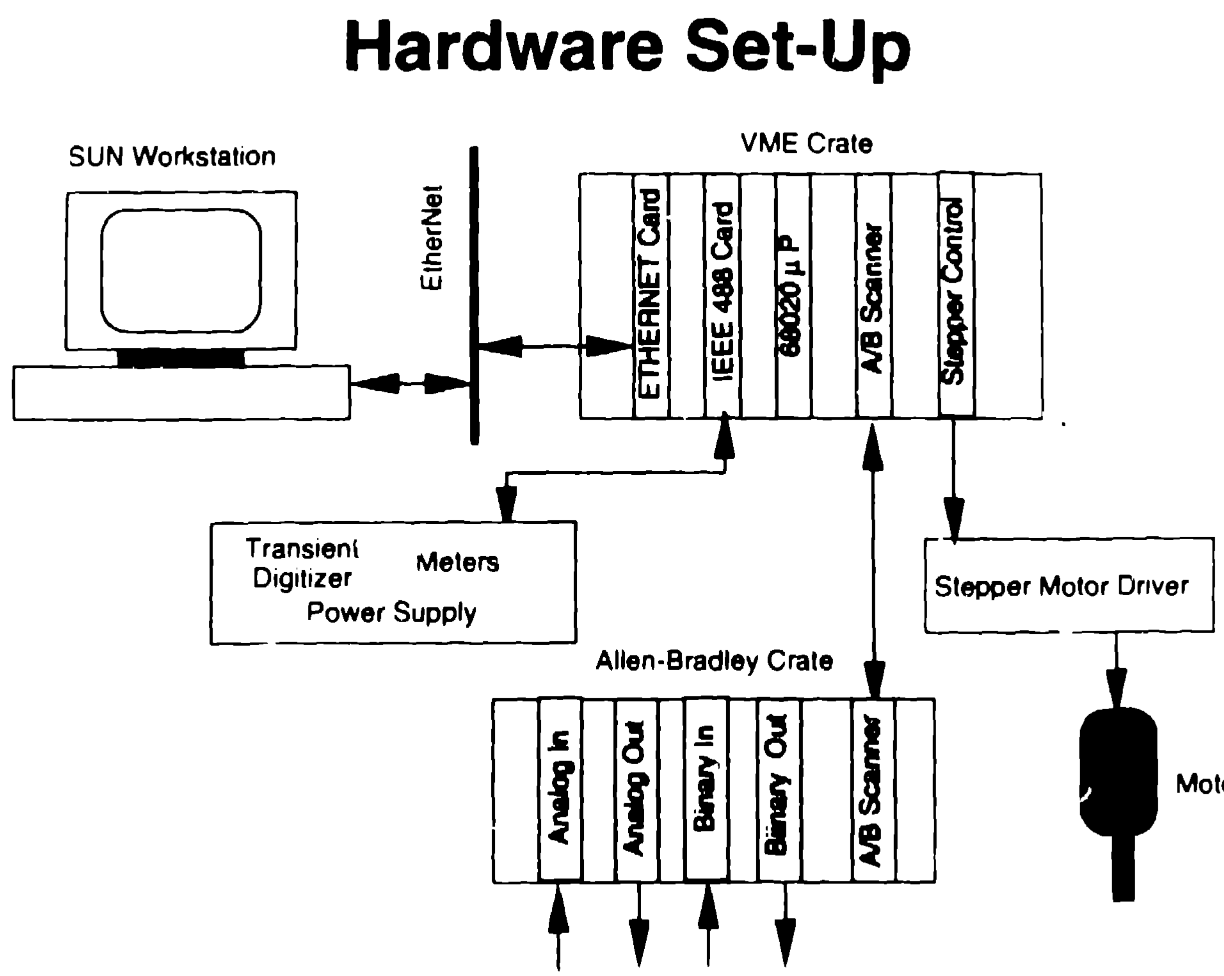

Fig. 10. Diagram of the hardware arrangement of the AFEL Control System.

Figure 11 is a schematic of the software environment[10]. A database contains information on all of the variables that are monitored by the system; these are called process variables. The database can be modified using the Database Configuration Tools and displayed graphically using the Operator Interface. Programs can be written using the State Notation Language to conditionally and sequentially control process variables. The database is stored on a hard disk using the Archiver.

There are many advantages to using a computer-based control system. The system can be reconfigured more flexibly when changes of hardwares and modifications are made. Control can be added piecemeal. Different experimental areas, such as the drive-laser room, the klystron gallery, and the vault, can readily communicate using Ethernet. Data can be easily archived and made instantly accessible to various users simultaneously.

7. FEL OSCILLATOR

Initially, a 15-cm permanent-magnet wiggler will be used. The wiggler period will be 1 cm and the selected FEL wavelength will be 3.7 µm. The length of the resonator is 1.4 m. Resonator mirrors are 1 in in diameter. We will use both broad-band silver mirrors and narrow-band multilayer dielectric mirrors at different times. We expect the following FEL performance: a small signal gain of up to 300%, and a micropulse-averaged power of 1.85 GW with an extraction efficiency of 4%.

At a later stage, we will use electromagnetic microwigglers. Some of which will be 12 cm long with 3-mm periods and have a double-helix design[11]. It will be driven by a pulsed dc current of 10 kA to generate a magnetic field up to 5 Tesla on axis. This microwiggler will produce laser light of 1.8 µm. By operating at higher harmonics, we can reach submicron laser wavelength. At the fifth harmonic (0.36 µm), a small-signal gain above 150% is predicted.

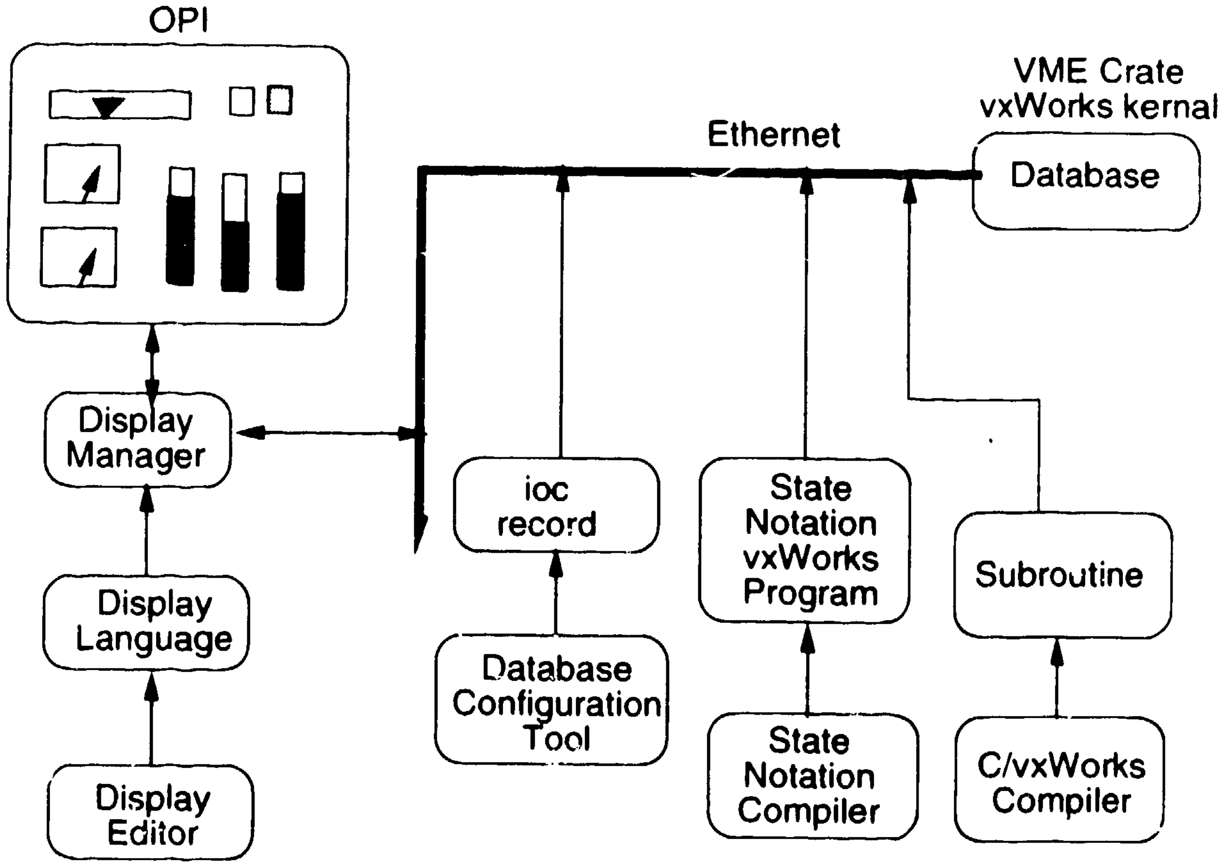

Fig. 11. Schematic diagram of the software environment of the AFEL Control System.

8. PRESENT STATUS

The facility and the high-brightness accelerator are now under construction. Other subsystems are at various stages of final design. We expect the high-brightness accelerator to be operating by November 1991.

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