

DESIGN AND INITIAL OPERATION OF THE ETA-II INDUCTION ACCELERATOR*
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ETA-II is a high current, high-repetition-rate induction linac designed for use in free-electron laser (FEL) research. ETA-II design is to produce 7.5-MeV, 2-kA, 70-ns pulses at a brightness of 2×10^9 A/(m-rad)² with a repetition rate of up to 100 Hz continuous or 5 kHz in a burst mode. The pulse power is generated by pulse compression using magnetic switching. The accelerator consists of a 1.5-MeV injector using an M-type dispenser cathode followed by 60 induction cells. Each cell adds 100 keV to the beam.

ETA-II will be used for brightness transport studies needed for the design of higher energy accelerators for visible-light FELs. ETA-II will also drive a microwave FEL at 140 GHz and 250 GHz for plasma heating experiments in a tokamak. This report will describe the design parameters and initial operation of ETA-II.

Introduction

ETA-II was built to demonstrate the capability of induction linacs to operate at high average power for long pulse bursts and to accelerate and transport high brightness electron beams. The motivation is to advance the technology of induction linacs as drivers for free-electron lasers. ETA-II will also be used as a driver for a microwave FEL operating at 250 GHz for 0.5 s at an average power of 2 MW. The microwaves will be used for electron cyclotron resonance heating in the MTX tokamak at Lawrence Livermore National Laboratory (LLNL). Present operating and design goal parameters for these two missions for ETA-II are given in Table 1.

The 70-ns pulse has a 50 ns flat top. In the longer term, it is planned to extend the beam energy to 10 MeV and the burst length to 30 s.

Accelerator Design

The ETA-II accelerator consists of an injector followed by 60 accelerator cells all installed in a concrete radiation-shielding vault. The accelerator cells are configured in blocks of ten. Between each 10-cell block is a short section that provides access for vacuum pumps and beam diagnostics. An individual cell is shown in Fig. 1. The high voltage pulse is introduced to each cell on two sides from a high voltage bus that runs the entire length of a 10-cell block. A high density alumina insulator provides the vacuum interface between beampipe and dielectric fluids in the pulse power

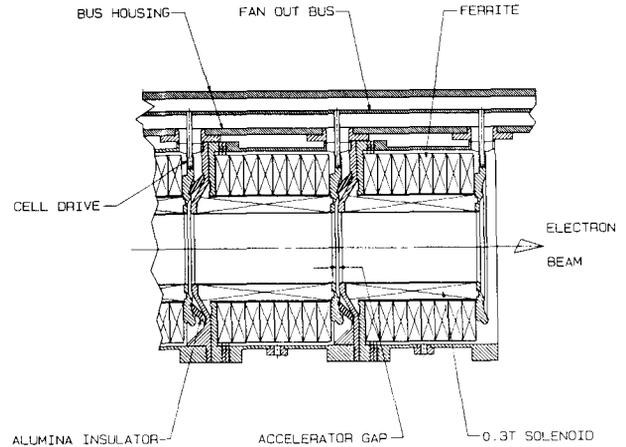


Fig. 1. Individual accelerator cell

feed system and ferrite cavity. The vacuum seal is made with O-rings compressed against the flat ends of the ceramic insulator. A solenoid embedded in each cell magnetically focuses the beam throughout the accelerator. Wrapped around each solenoid is a printed circuit trim coil with a sine-cosine winding distribution that produces a uniform B_x and B_y . Reference 1 describes design issues that determined the shape of the accelerator gap and the diameter of the beampipe.¹

Figure 2 shows the 10-cell accelerator module. The cells in the module are mounted on a rigid strongback that provides a stable reference for aligning each cell. The module is mounted in a stainless steel cradle with five screw jacks in a three-point support pattern. This entire assembly is then mounted on a pair of 37.5 mm precision rails that run the length of the accelerator. The rails are supported every 3 ft. by pedestals anchored to the concrete floor.

The intercells between each 10-cell block are 457 mm long. Each has a 1000-1/s turbomolecular pump and an 8-in. cryo pump. Access ports on the top and bottom allow diagnostic devices to be inserted into the beam. For example, a foil can be inserted to view the beam current distribution. Each intercell also has a beam current monitor that gives time-resolved beam current and beam centroid position data.

Table 1. Present operating and eventual design parameters for ETA-II

Parameter	<u>Brightness Studies</u>		<u>Microwave FEL</u>	
	<u>Achieved</u> ^a	<u>Design Goal</u> ^b	<u>Achieved</u> ^a	<u>Design Goal</u> ^b
Beam energy (MeV)	6	7.5	7	7
Beam current (kA)	0.8	1.5	2	2.5
Beam brightness [A/(m-rad) ²]	6×10^8	2×10^9	1×10^8	1×10^8
Pulse repetition frequency (Hz)	1	5×10^3	1	5×10^3
Burst length (s)	—	0.01	—	0.01

^aAs of October 1, 1988

^bFor October 1, 1989

Auxiliary Systems

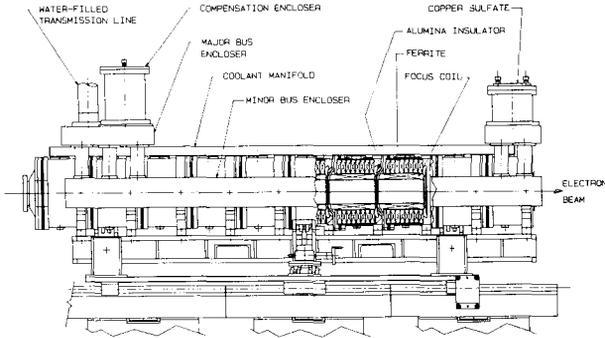


Fig. 2. 10 cell accelerator module

The ETA II injector, shown in Fig. 3, consists of nine cells similar in construction to the accelerator cells. The four cells on the anode end have the anode beampipe running through the center. The five cathode cells require no focusing solenoids. The ferrite cores fill the coil space and can have the same cross sectional area of ferrite in a shorter length. The cathode support stock runs through the cathode cells. Mounted on 200 mm diameter ports around the center spool are two 8 inch cryo pumps and two 1000 l/s turbomolecular pumps.

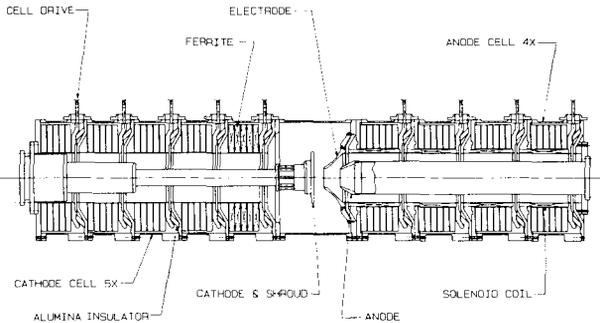


Fig. 3. ETA II injector

The electron gun is a triode configuration consisting of an 88-mm-diam M-type dispenser cathode, an intermediate electrode, and an anode. The cathode, with a 246 mm spherical radius, is surrounded by a focusing electrode. It is mounted on the cathode stock that carries the heater current wire and the water that cools the cathode housing. The intermediate electrode separated from the cathode by 52 mm is mounted on the anode cell next to the spool. The anode pipe is 150 mm in diameter and can accommodate up to 150 mm diameter cathodes. In the present configuration the anode tip is located 118 mm from the cathode.

Auxiliary systems are located on a covered pad outside the main accelerator building. On the pad are located mechanical vacuum pumps that provide for rough pumping the beamline, for foreline pumping for the turbomolecular pumps, and for regenerating the cryo pumps. The vacuum lines run from the pad into the accelerator vault and run the full length of the accelerator and the beamline for transporting the beam to the brightness and beam energy diagnostics and to the microwave FEL. Separate mechanical pumping systems serve the injector and accelerator. The beamline vacuum must reach a base pressure of 1×10^{-6} Torr in the accelerator beampipe and less than 1×10^{-7} Torr in the injector section. A deionized water system provides 100 l/min of 15-M-cm water for use as the dielectric in the high voltage capacitor of the magnetic pulse compressors (MAG 1-D) and 4-ohm transmission lines that deliver the pulse power to the accelerator. Copper sulfate is the resistive medium in compensation networks which match the pulse power transmission line impedance to the load impedance. When ETA II is configured for high average power, it will require copper sulfate to flow at 2100 l/min to the accelerator and 1300 l/min to the injector. The two systems require different concentrations to perform the impedance matching. Other systems cool the other dielectric fluids such as Freon 113 or Flourinert in the accelerator and the MAG 1-Ds. Low conductivity water (LCW) circulated throughout the building cools the focus solenoids and all heat exchangers that use closed-loop primary fluids.

Pulse Power

ETA-II requires four power conditioning chains to drive the injector and 60 accelerator cells. A block diagram is shown in Fig. 4. A MAG-1-D drives either the injector or 20 accelerator cells. The voltage waveforms for a single power-conditioning chain are shown in Fig. 5. Thyatron modulators charge the inputs of the MAG-1-Ds to 25 kV in 3.7 μ s. The MAG-1-D compresses this charge pulse to 70 ns FWHM and steps it up to 125 kV. The drive pulse is delivered to the accelerator cells through two 4- Ω water-filled transmission lines. Each power-conditioning chain is independently timed, and the timing of accelerator cell sets driven by a common MAG-1-D is set by the length of the 4- Ω transmission lines.

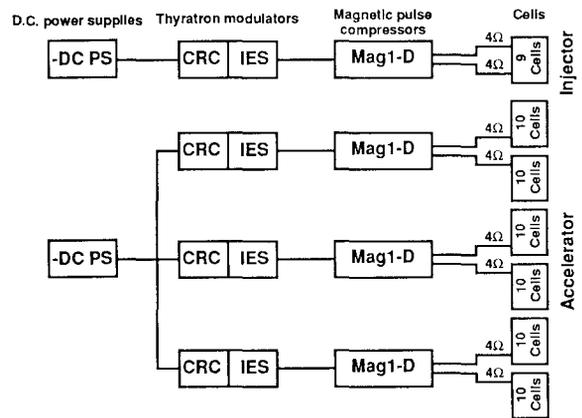


Fig. 4. Pulse power chain

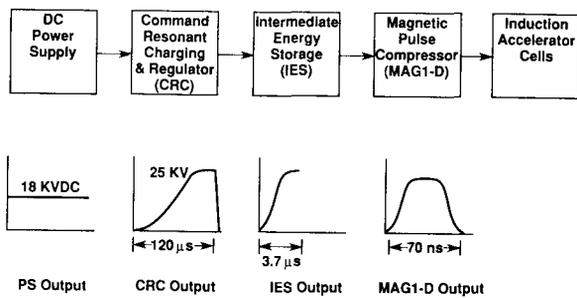


Fig. 5. Pulse power waveforms

Figure 6 is a simplified schematic of the thyatron modulators. The modulators use a command resonant charge (CRC) circuit to charge the 2- μ F intermediate energy storage (IES) capacitor to 25 kV in 70 μ s. The IES capacitor is then discharged by four EEV CX1547 thyatrons into the 2- μ F input capacitance of the MAG-1-D. The thyatron modulators are capable of charging the MAG-1-Ds at 5 kHz for 30 s, which corresponds to an average power of 3 MW.

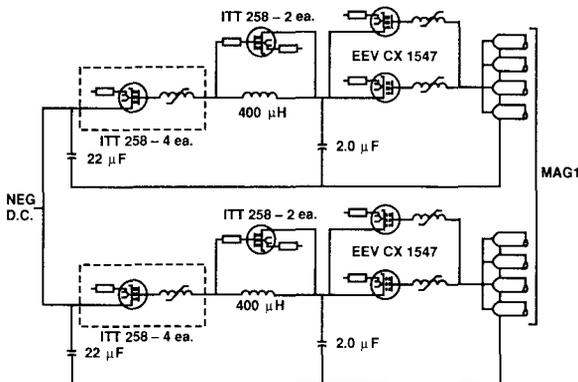


Fig. 6. ETA II thyatron modulators

The MAG-1-D uses two stages of magnetic pulse compression to charge a 2- Ω water dielectric pulse forming line (PFL) in 250 ns. The PFL, which is 35-ns long, is discharged through a magnetic switch into the accelerator cells, which provides a 70 ns FWHM accelerating pulse with a risetime of approximately 20 ns. Direct current power supplies reset the magnetic switches between pulses. Circulating Fluorinert cools the magnetic cores during high-repetition-rate operation.

Output pulse timing is critical for proper accelerator operation. Pulse-to-pulse timing variations must be less than ± 1.25 ns. Timing variations arise from several sources within the power conditioning system. The most obvious source, and perhaps the easiest one to deal with, is thyatron jitter. We reduce thyatron jitter to subnanosecond levels by using dc filaments on the thyatrons and by using a 2-kV trigger pulse with a 50-ns risetime.

A second source of accelerator drive pulse jitter is variation in the charge voltage at the input to the MAG-1-D. This occurs because $\int V_{in} dt = \text{const.}$ for a magnetic pulse compressor, where V_{in} is the input charge voltage, and T is the time delay through the magnetic pulse compressor. We have two methods for controlling jitter resulting from input voltage variations. First, the input voltage to the MAG-1-D stays regulated to within 0.4%, which is consistent with the requirement for beam energy regulation. Second, we are resistive de-Qing in the CRC circuit to regulate the IES capacitor voltage. To achieve ± 1.25 ns timing variations without imposing unrealistic voltage regulation requirements, we are developing a second method of jitter reduction that uses a simple electronic circuit to vary the IES thyatron trigger time as a function of IES capacitor voltage. This circuit provides a variable delay that compensates for changes in delay through the MAG-1-D resulting from input voltage variations. Jitters of ± 1 ns have been achieved. Either one or both methods may be required for long duration, high-repetition-rate bursts.

A number of engineering problems must still be solved before we can reliably accelerate an electron beam at 5 kHz. Although we have demonstrated high-average-power operation of a single modulator system for short periods, we must do more development work to address long-term thermal drift problems and high-repetition-rate reset problems.

Control System

The controls system centers around a workstation with two microVAX-II computers that are used to control thousands of set points as well as the interlocks required for machine protection. The control room contains the consoles and diagnostic displays operators use to run the accelerator. Each of eight operator consoles has a color graphics monitor, overlay touch panel, and software-programmable knob chassis that can access and control all accelerator functions. The touch panels and knob chassis control such functions as opening valves in the vacuum system and turning on and adjusting the voltage of power supplies that drive the focus coils, steering and trim power supplies, and pulse power systems. In addition, the touch panel interface monitors and controls all auxiliary systems. The control system supports several I/O standards including Modicon, CAMAC, and GPIB. The Modicon-programmable controllers automatically protect against such events as component failures or the inadvertent opening or closing of a valve that may harm the accelerator. The Modicon controller also controls the safety interlock system for the radiation shield vault and displays the status of door interlocks and radiation monitors on one of the color monitors in the control room. Operator and hardware connect through a "shared section" of the computer memory which contains the current state of every control and monitor value in the accelerator. The scanner process writes Modicon data into the shared section as rapidly as possible. The console reads data from the shared section and updates the operator displays. Splitting up the write and read functions in this way optimizes each and provides the best overall performance. The archiver and alarmer both use information in the shared section to perform their own functions. The archiver will, upon request, store the setpoints for all controls, thus allowing the machine conditions to be easily restored. The alarmer will log an error message or announce it on Dectalk when it detects a fault condition.

Alignment

The accelerator, FEL wiggler, and transport and diagnostic devices are mechanically aligned to a beamline that is established by a precise survey of the shield vault. Survey monuments permanently installed throughout the vault allow a transit to be set up with known relationship to the beamline. The rails supporting the accelerator were installed with a transit. The injector and each 10-cell block of the accelerator were then mounted on the rails and aligned to the beamline by adjusting the jack screws on the three point mounting system. The center of the beampipe was defined for this adjustment by centering removable targets in each end of the block. More important to the stable transport of the electron beam is the precise alignment of the magnetic field over the length of the accelerator. Small perturbations in the alignment of the individual focus coils and the transverse residual effects of the leads and transitions in the coil windings can be effectively compensated by the trim coils installed around each focus coil. To determine the field alignment and provide a basis for adjusting the trim coils, we first launch a low energy electron probe down the center of the beampipe. The electron beam, which follows a flux line of the solenoid transport, is monitored by a TV camera viewing a phosphor-coated glass. The camera is mounted in a cart that is pulled through the beampipe with the phosphor screen fixed to the front of the cart.

The mechanical axis is defined by a helium-neon laser that is aligned to the vault beamline. The displacement of the e-beam with respect to the laser determines the field error. Trim coils are then individually energized to minimize the observed field error.

Each 10-cell block and the anode end of the injector was checked for magnetic alignment with a cart that ran on stainless steel rails over the length of the block. The results of this alignment process are shown in Fig. 7. The coil input leads create most of the 0.1-mm periodic ripple. This effect can be eliminated in future designs by a quadrifilar solenoid design.

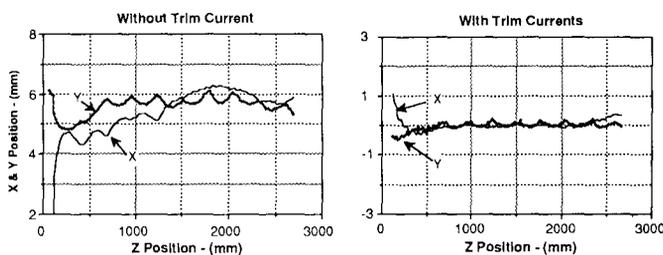


Fig. 7. Effect of trim coils to align the magnetic field.

The low energy e-beam probe has been modified to permit travel over the full length of the accelerator. This device, shown schematically in Fig. 8, will be used to mechanically align and trim the intercell coils as well as the 10-cell blocks. The trim currents derived from a full-length scan with this low energy electron-beam are stored in the control computer and define a correction current ratio that is used to maintain the correct trim current as the focus coil currents are varied.

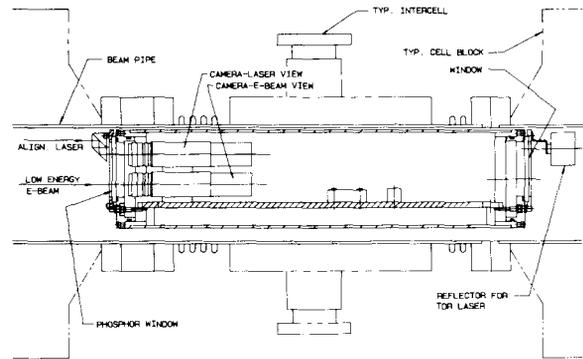


Fig. 8. Low energy electron probe

Diagnostics

The ETA-II diagnostics system provides on-line real-time measurement and display of key beam parameters to assist in tuning the accelerator and to acquire and store key physics parameters by which the overall performance of the accelerator may be determined. Two different types of diagnostics systems are used. The first, a trace acquisition system, consists of multiple high speed transient digitizing oscilloscopes which capture electrical waveforms. The second, a video-based system, captures two-dimensional video images of the electron beam as it passes through various types of diagnostic foils. The video diagnostic system uses very fast time-gated microchannel plate image intensifier television cameras to view the targets.

Resistive wall current monitors measure beam current amplitude and position. Voltages in the pulse power chain and the accelerator bus systems are measured with capacitive voltage probes.

Both the trace and video diagnostics systems are controlled through a MicroVAX-II workstation. The multi-window user environment allows on-line acquisition and analysis of diagnostic trace and image data, as well as archiving data for later, off-line analysis. A common diagnostic user interface is maintained at all LLNL Beam Research Program facilities for versatility in data analysis. The diagnostics computer is networked with the control system computer and is able to acquire and correlate machine state data with diagnostics measurements.

Initial Experiments

Initial operation of ETA-II with the Injectron injector began in January 1988 and continued through May 1988. Operation was stopped for final alignment of the magnetic field with the low energy electron probe and for vacuum system modifications.

An 88-mm-diam M type dispenser cathode was used as the initial electron source. The injector was developed at the LLNL Accelerator Research Center facility before being installed in ETA-II. At the ARC, Injectron produced 1400 A at 1.3 MV. The peak brightness was 2.0×10^{19} A/(m-rad)². In ETA-II using the same gun configuration the same current and voltage were obtained. However, because the cathode had to be run at 1280°C, emission life was only a few hours. With the full accelerator

operating, an emission limited current of 800 A was transported. Peak current was preserved in transport. However, the current pulse narrowed significantly because of beam losses in the head and tail of the pulse that arose because the accelerator transport has a reduced acceptance for the lower energy beam in the rise and fall of the pulse.

To determine why the cathodes ran hotter in ETA-II than in ARC, we used a residual gas analyzer to study the vacuum. We found that Freon 113, which was used as the cooling and dielectric fluid surrounding the ferrite in the cells, was diffusing through the Buna-N O-rings sealing the ceramic insulator. The Freon vapor poisoned the dispenser cathodes and caused the high temperature operation and resultant short life.

For further tests, we replaced the dispenser cathode with a velvet cathode. An 88-mm-diam velvet cathode produced 1200 A from the injector. A current of 1000 A was transported through the accelerator. The beam current is shown in Fig. 9. The current out of the injector is shown in (a) and the current out of the accelerator is shown in (b). The loss of the beam current in the head and tail is evident here. The FWHM pulse width is 75 ns out of the injector and 45 ns out of the accelerator.

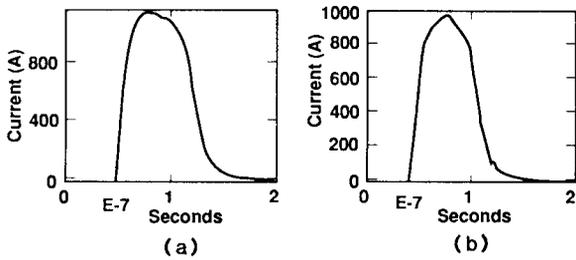


Fig. 9. Beam current out of injector, through the accelerator

We measured beam brightness with two apertures separated by a 580-mm drift distance. Current was measured in the front and back of each aperture. The results of these brightness measurements are shown in Table 2.

Table 2

Dispenser 800 amp emission limited 88 mm dia.	Velvet	
	88 mm	50 mm
$J = 6.3 \times 10^8 \text{ A/(m-rad)}^2$	$<1 \times 10^8$	3.3×10^8

Further brightness transport measurements will be made on a 1500-A beam from a dispenser cathode after the magnetic alignment and vacuum improvements are completed. The injector is being refurbished with viton O-rings and will use Fluorinert 75 as the dielectric fluid. These improvements should reduce the potential for cathode poisoning.

*Performed jointly under the auspices of the US DOE by LLNL under W-7405-ENG-48 and for the DOD under SDIO/SDC-ATC MIPR No. W31RPD-7-04041

Reference

1. G. J. Caporaso, 1986 Linear Accelerator Conference Proceedings SLAC Report 303, pp 17-20, Sept. 1986.