INDUCTION LINAC-BASED FELs

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Abstract

The multikiloampere peak currents available from linear induction accelerators make high-gain, free-electron-laser-amplifier configurations feasible. High-extraction efficiencies in a single pass of the electron beam are possible if the wiggler parameters are appropriately "tapered," as recently demonstrated at millimeter wavelengths on the 4-MeV ELF facility. Magnetic pulse power systems enable high-repetition-rate operation of the accelerator for high-average-power applications. Key issues involved in extending the technology to shorter wavelengths and higher average power are described.

1. Introduction

Induction linacs (IL) are capable of multikiloampere peak currents. This capability has stimulated the investigation of single-pass free-electron laser (FEL) amplifiers with very high gain and high conversion efficiency. Experiments on the tapered wiggler concept for achieving high conversion efficiency met with dramatic success on the 35-GHz microwave experiments on the Electron Laser Facility (ELF).[1] Current efforts are focused on extending these results to much shorter wavelengths on the 50-MeV PALADIN experiments on the Advanced Test Accelerator (ATA).

An overview of the induction linac-based FEL master oscillator-power amplifier (MOPA) is given in Section 2. The fundamental physics issues involved in the tapered wiggler operation are described in Section 3, with particular emphasis on explaining the requirements of small electron-beam energy spread and high brightness for efficient energy conversion. Current efforts to achieve high-brightness-beam generation and acceleration are summarized in Section 4, and the high-repetition-rate power systems that enable the high-average-power capability of IL-FELs are described in Section 5. Conclusions are offered in Section 6.

2. General Description of Induction Linac-Powered FEL Amplifiers

A schematic showing the various elements of a single-pass MOPA FEL configuration driven by an induction accelerator is presented in Fig. 1. The induction accelerator is basically a linear series of pulse transformers that individually give an increment of voltage to the electrons as they pass down the axis of the system. The pulse lengths of the acceleration voltage are generally chosen by compromising between the desire to minimize the magnetic material volume (V-s) and the need to maintain an adequate flat top on the acceleration waveform. These compromises result in pulse lengths of 50-70 ns in current systems. High average power is obtained by operating at high pulse-repetition rates; the magnetic modulator systems described in Section 5 are technologies that will enable us to meet this objective.

The electron-beam pulses from the accelerator are sent through the wiggler, then discarded in a beam dump. A drive laser (or microwave source) sends input pulses in synchronism with the driving electron-beam pulses. The front section of the wiggler has uniform properties, acting as a linear amplifier (a "preamp") for the input laser. The electromagnetic power increases exponentially with distance up to the point where the electrons are "trapped" by the wave—at this point the electron beam is strongly bunched in "pancakes," periodic at the input signal wavelength (Fig. 2). Beyond this point, the wiggler properties must be tapered with distance to extract a significant fraction of electron-beam energy (tens of percent), as explained in Section 3.

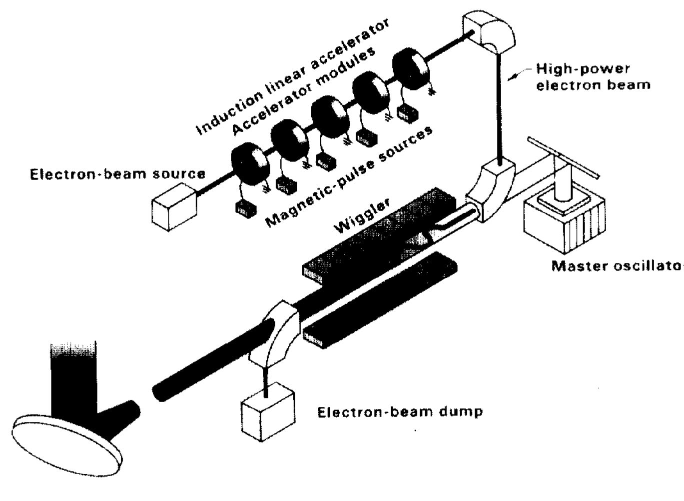

Fig. 1. Component technologies for induction linac FEL amplifiers.

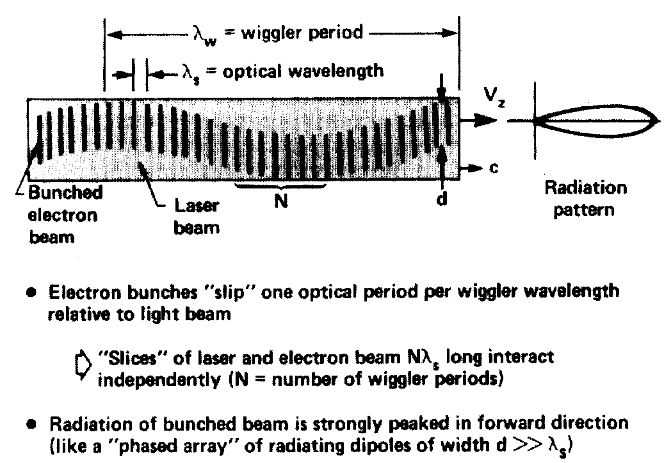

Fig. 2. Physical picture of FEL amplifier operation.

The radiation from the "pancake bunches" of relativistic electrons is highly peaked in the forward direction. This is because of the usual relativistic dipole radiation pattern (cone of angle $\sim 1/\gamma$) and also because the individual electron's dipole radiation is also summed over the "pancake" of radial width $d \gg \lambda$, thereby acting like a "forward-fire" phased-array antenna. The overall result is that a free-electron laser has a gain pattern that is *highly* peaked in the forward direction. Many of the usual limitations on the maximum gain per module do not apply to the FEL, because oscillations from "spurious modes" with transverse gain are absent. The pulsed nature of the

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driving electron beam also simplifies greatly the handling of reflections in FEL amplifiers with very high gain. The experimentally demonstrated capability for 80-dB small-signal gain in the millimeter wavelength experiment (ELF) without spurious oscillations is noteworthy in this context. (We should note that growth of sideband frequencies that couple to the axial oscillations of electrons trapped by the wave is one of the few spurious modes of potential significance in this laser system.)

The optical beam output from the FEL amplifier can be expanded to a low enough power density for beam transport and beam directors to handle, even with the very-high-average powers that can be achieved at high-repetition rates. For example, in microwave systems it is not necessary to have output windows (in applications such as plasma heating or driving rf accelerators) because the vacuum conditions near sensitive components like the electron cathode are physically well isolated from the output waveguide.

The fundamental characteristics of induction linac-driven amplifiers are well suited for applications requiring very-high-peak- and/or average-power outputs from a single aperture. Electron beams of high power can be generated quite efficiently, and the "gain medium" consisting of electrons, dipole wiggler fields, and a vacuum pipe presents very few limitations on power or power density in the gain region.

The following sections will describe the developments needed for this promise to be fulfilled.

3. FEL Amplifier Physics

The proper operation of an FEL amplifier requires that one maintain a precise relationship between the longitudinal velocity of the electron beam and the wavelengths of both the electromagnetic radiation and the wiggler's magnetic field. This relation is given by:

$$\gamma_{\|} = \left(\frac{\lambda w}{2\lambda_s}\right)^{1/2} \pm \delta \ , \qquad (1)$$

where λ_s is the wavelength of the electromagnetic wave to be amplified, λ_w is the period of the wiggler, and $\gamma_{\|}$ is defined by:

$$\gamma_{\|}^2 = \frac{1}{1 - V_{\|}^2/c^2} \ , \qquad (2)$$

with $V_{\|}$ the longitudinal (axial) velocity of the electrons. The quantity δ represents the accuracy to which the electron's longitudinal energy must be held if a significant transfer of energy from the electron to the electromagnetic wave is to take place. Limits on δ depend on both the intensity and the wavelength of the light to be amplified, and these limits can range from a few percent at microwave wavelengths to a few tens of percent at optical wavelengths.

If an amplifier is to be efficient, a very-high-quality electron beam is required so that all of the electrons within the beam satisfy Eq. 1. This not only implies careful control of the beam energy but, in addition, mandates careful control of the beam's emittance (ϵ_n). One can estimate the emittance requirement by relating the emittance to the dispersion in axial velocities, which can be written as:

$$\frac{\Delta\gamma_{\|}}{\gamma_{\|}} = \frac{b_w \epsilon_n}{4\left(1 + a_w^2\right)} \ , \qquad (3)$$

where $b_w = eB\lambda_w/2\pi mc$, with B the peak wiggler magnetic field.

Once the electron beam requirements are satisfied, one is left with the problem of extracting large amounts of energy from the electron beam (several tens of percents) under the constraints of Eq. 1. Obviously if $v_{\|}$ ($\gamma_{\|}$) changes substantially as a result of electron beam energy loss, according to Eq. (1), the interaction will cease and the amplifier will saturate before significant energy extraction has occurred. A method for circumventing this limitation was first described by Kroll, Morton, and Rosenbluth; it is called the tapered wiggler.[1]

The tapered wiggler concept relies on having the wiggler properties vary as the electrons slow down, so that the resonance condition can be preserved while extracting large amounts of energy. The simple realization of this concept would be to decrease λ_w proportional to $\gamma_{\|}^2$, but operationally it is difficult to build wigglers with the requisite short periods at the downstream end. If one recognizes that:

$$\gamma_{\|} = \frac{\gamma}{\left[1 + 1/2\left(b_w/k_w\right)^2\right]^{1/2}} \ , \qquad (4)$$

however, one can see that the electron's total energy (γ) can be reduced without altering its parallel energy (thus maintaining resonance) by simultaneously reducing the wiggler's magnetic field, b_w. This is the approach taken in the design of ELF, a microwave FEL.

ELF was specifically designed to test the tapered wiggler concept as described by Kroll, Morton, and Rosenbluth.

The ELF experiments showed that untapered efficiences of 5-6% could be increased to 40% by appropriately tapering the profile of $b_w(z)$, in good agreement with the modeling.[2] Also ELF has shown high exponential gain (in the small-signal regime) in accordance with theoretical predictions. Utilizing tapered wigglers, these experiments demonstrated high gain (greater than 42 dB) even when operating at high-power levels, i.e., one can make the transition from small signal gain to large signal gain in a single device.

ELF is unable to test certain aspects critical to the operation of an optical FEL. First, one must change the method of transporting or focusing the electron beam. Quadrupoles (as used on ELF) would cause a loss of efficiency. Curved pole pieces are essential for operation of a linearly polarized wiggler and will first be tested on the 10.6-μm wavelength experiment on ATA (PALADIN).

Second, ELF is a microwave amplifier operated in a waveguide; therefore, it is unable to address the questions of optical guiding and optical mode control that will be addressed on the PALADIN experiments.

In summary, ELF has demonstrated the validity of the tapered wiggler concept. The PALADIN experiments currently underway are intended to show that those concepts are also valid at optical wavelengths.

4. High-Brightness Electron Beams

Over the past two decades, LLNL and the Lawrence Berkeley Laboratory (LBL) have collaborated in the development of several linear-induction accelerators (LIA). These include the Astron (6 MeV, 0.5 kA, 300 ns), the ERA (4 MeV, 1.5 kA, 30 ns), the ETA (5 MeV, 10 kA, 30 ns), and the ATA (50 MeV, 10 kA, 70 ns). The primary requirement of this accelerator development has been to achieve high-beam currents, with relatively little concern for beam emittance. The FEL application for LIAs, in contrast, places a very high premium on beam brightness and on high-average-power operation. The technology for these requirements is being developed on the Accelerator Research Center (ARC) accelerator (2 MeV, 0.8 kA, 50 ns, and multikilohertz repetition-rate capability). The brightness of an electron beam (the beam's density per unit 4-volume of phase space) is defined as

$$J[A/(\text{rad-cm})^2] = \Psi\, I/\epsilon_n^2 \ ,$$

where I is the beam current, ϵ_n is the normalized edge beam emittance ($\beta\,\gamma RR'$), and Ψ is a shape factor (for uniform density ellipsoids in phase space, determination of edge emittance specifies $\Psi = 2$). Using conservation of momenta ($m_o V_{(source)} = \gamma\, m_o\, v\_$) and $\beta = v_z/c$, we can describe the lower bound on beam emittance as it leaves a "perfect" (a smooth and uniformly emitting) cathode plane of temperature T_e and radius R,

$$\varepsilon_n = \beta\gamma R R' = \beta\gamma R \frac{v_\perp}{v_z} = R \frac{v_{(source)}}{c}$$

$$= 2 \times 10^{-3} R_{cm} \sqrt{T_{e\,(source)}^{(ev)}}$$

Obviously, the "perfect" cathode source for high brightness requires a low effective temperature and a high extraction-current density (small radius). Our injector development program, which has as its goal beams of 2×10^6 A(cm-rad)^2 normalized brightness at 3 kA to meet the requirements imposed by Eqs. (1) and (3), has explored various cathode technologies to quantify these operating parameters. Of equal importance, we are trying to determine how requirements of continuous high power and high-repetition-rate operation compromise the performance of various cathodes. In Table 1, we briefly summarize our findings. As is apparent from Table 1, our current research is concentrating on the dispenser cathode primarily because this technology is best able to generate high-brightness beams and satisfy the reliability requirements of high-average-power, high-repetition-rate operation.

The operating parameters of a high-current/high-brightness injector are determined by the following two requirements, which incorporate the criteria set by preservation of the normalized cathode emittance in the subsequent transport and acceleration processes.

1. The extraction electric field E (= V/d where V is the injector voltage and d is the cathode-to-anode gap spacing) has a practical upper limit if one is to prevent unwanted emission from noncathode surfaces. Even modest electron emissions from such regions, when combined with those originating from the cathode, drastically increase emittance and pose serious problems to stray power management in high-average-power operation. Our initial high-average-power tests at full repetition rates indicate limitations of E = 120 kV/cm for satisfactory operation.

2. Increases in beam emittance during transport stem from the coupling of space-charge fields to the beam-particle trajectories. Beams with uniform profiles minimize this coupling. To ensure uniform cathode emission, the ratio of cathode radius, a, to gap spacing, d, appears to have a limiting value. An estimate of the limiting value of a/d determined by extensive numerical simulation is $a/d \leq 1/3$. These simulations seek to optimize beam parameters of cathode radius a, gap spacing d, the anode bore size (effective hole in the anode through which the beam is extracted), the z-variation in transport axial magnetic field (to avoid angular momentum, the axial magnetic field is zero on the cathode surface and then increases to full focusing strength), the injector voltage V, and geometric shapes of all cathode-anode-electrode components.

The total beam current is determined by $I = \pi a^2 j$, where j is the current density (assumed to be uniform according to criterion 2). Note that

$$j = K(\gamma) \frac{V^{3/2}}{d^2}$$

where K is the perveance, which includes relativistic and anode-depression corrections.

Table 1: Study of cathodes for high-brightness and high-average-power operation.

Cathode type	*Description*	*Summary*
Plasma surface discharge	**Many small sites of surface electrical discharge; energy per discharge site is low and controllable**	**• Good current density (>20 A/cm^2) and uniformity • Rugged and reliable repetition-rate operation • Poor beam emittance due to granularity and high effective temperature of emitting plasma sheath**
Field emission	**Surface ionization and/or wisker vaporization forms cathode plasma**	**• Good current density • Dense plasma closure of anode-cathode gap limits repetition rate • Emittance and uniformity uncertain • Degrades under high-average-power operation**
Occluded, gas-enhanced field emission	**Velvet cloth as large surface area gas source with fibers giving field enhancement**	**• Good current density (50 A/cm^2) • Uniformity of emission degrades with lifetime • Beam brightness few × 10^5 • Plasma closure limits repetition rate**
Thermionic emitters	**Low work function triple-oxide coatings on heated surfaces**	**• Limited current density (~10 A/cm^2), but with good uniformity, beam emittance unknown • Taxing vacuum requirements and highly susceptible to poisoning • Thermal stresses weaken bond of oxide to supporting substrate • Not mechanically reliable under high-power operation**
LaB_6	**Low work function material heated to very high temperatures (2400 K)**	**• Good current density (50 A/cm^2) and uniformity, emittance unknown • Very delicate to thermal stresses • High-average-power operation untested**
Dispenser	**Low work function barium-impregnated surfaces heated to elevated temperature (~1100 K)**	**• Good current density (20 A/cm^2) and uniformity • Beam brightness > few x 10^6 • Reliable operation at full repetition rate • Taxing vacuum requirements**
Photo-emission	**Laser-irradiated surface**	**• Untested, known to have good current density and uniformity but total current and charge (surface area and pulse duration) are limited • Testing for high-repetition-rate operation requires major investment in laser development**

To explicitly display the limiting parameters, we write the current as

$$I = \left[\pi K \left(\frac{a}{d}\right)^2 E^{3/2}\right] d^{3/2} \quad .$$

This result numerically implies that if I = 3 kA is the goal, gaps of 25 cm driven at 3 MeV are required. Thus far, the ARC facility has achieved the following performance parameters, utilizing dispenser cathode technology and simultaneously achieving high-average-power operation:

- Beam current 0.8 kA
- Injector voltage 0.8 MeV
- Post acceleration 1.2 MeV
- Beam brightness measured at 2.0 MeV, 1.3×10^6.

The future course of our research is to develop the engineering technology toward higher voltage injector operation (3 MeV), to allow increased beam current. This work will continue to be done on the ARC facility and on our upgraded ETA accelerator (ETA-II). ETA-II, scheduled for initial operation in October 1987, will begin with a 1-kA, 8-MeV, 50-ns electron beam of high brightness (1.3×10^6) and operate at multikilohertz repetition rates for several seconds' duration, with an eventual goal of 3-kA at 2×10^6 brightness (see Section 5). The purpose of ETA-II is to integrate all aspects (physics and engineering) of high-average-power, high-brightness electron beam accelerators into one test facility.

5. High-Average-Power Technology

The generation of intense relativistic electron beams requires low-impedance, pulse-compression devices to provide the short (70-ns) acceleration voltage pulse. The spark-gap-based system has served the program well on both the ETA and ATA accelerators. It was recognized even during the construction of the ATA accelerator that the limitations of spark gaps in repetition rates (duty factor) and reliability would not allow us to apply this technology to high-average-power systems.

A development effort was initiated during the ATA construction to find a longer term replacement for the spark-gap-driven Blumlein, which we hoped would be deployable as an upgrade on ATA. This effort was accelerated when the FEL program became a major national effort. FEL applications place very stringent requirements on the power-conditioning systems. Those requirements drive us toward higher repetition rates, higher efficiency, better energy regulation during the acceleration pulse, and higher accuracy in alignment of components.

In order to generate the required 10-GW acceleration pulse for near-term systems, we are utilizing the well-tested magnetic pulse compressor, MAG-I-D. Although this pulse-compression scheme has been around for a number of years, it was only recent advances in magnetic materials and technology that allowed us to apply it to the generation of nanosecond pulses with efficiencies exceeding 90%. This technique consists of using the large changes in permeability exhibited by saturating ferromagnetic materials to produce large changes in impedance. This energy compression scheme allows us to utilize state-of-the-art switches (thyratrons, silicon-controlled rectifiers) to initiate the pulse at the 100-MW level and compress it to the 10-GW levels required by the accelerator. Because the compression cycle utilizes strictly passive devices (L's and C's), when properly designed its lifetime exceeds 10^9 cycles.

The current magnetic-drive system is shown in Fig. 3. It consists of an intermediate store switch chassis (ISSC), a pre-compression stage, a step-up transformer, the first stage of compression, and the final stage of compression that delivers the pulse-forming line energy to the accelerator in the form of a 70-ns pulse at 125 kV through two 4Ω lines (Fig. 4).

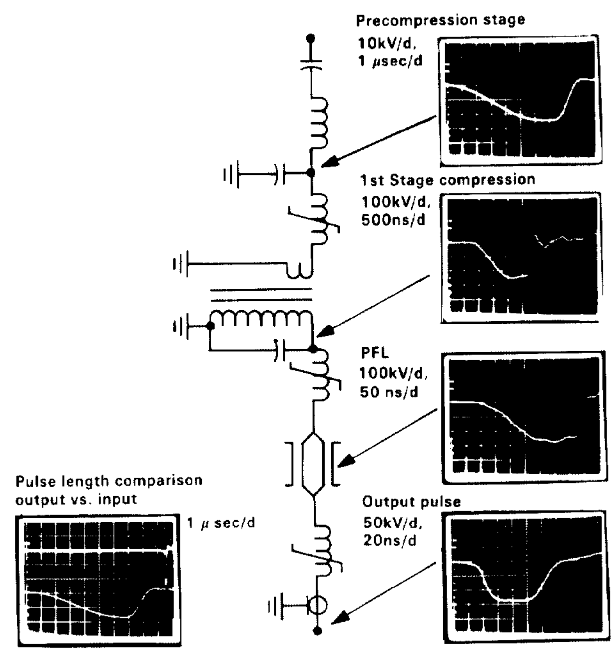

Fig. 3. MAG-I-D voltage waveforms.

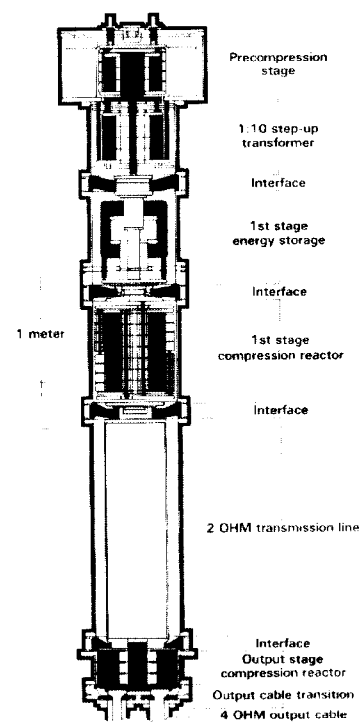

Fig. 4. MAG-I-D power compressor.

This system has been utilized during the past two years to generate the high voltages required by the injector in the ARC for studies of high-brightness, high-current beams. The ARC facility has been used for the generation of high-brightness beams (see Section 4) and for the development of these high-average-power drivers. The beam from the injector was accelerated through two ten-cell modules (Fig. 5) for a total energy of 2-3 MeV at the point where the brightness measurements were performed.

The stringent peak-power and repetition-rate requirements are stressing the capabilities of current state-of-the-art thyratrons. To date we have achieved 2.5-kHz repetition rates at nearly full-power output. In order to achieve our goal of 5 kHz, we have adopted the "Gatling-gun" mode of operation where two ISSC are fired in sequence at 2.5 kHz. This technology is currently undergoing extensive testing and will be applied on a large scale to the upgrade of the existing ETA accelerator described in Section 4. On March 1 of this year, the ETA was shut down and is in the process of being rebuilt as a 7- to 8-MeV accelerator using the new high-brightness injector and an all-magnetic drive system as illustrated in Fig. 6.

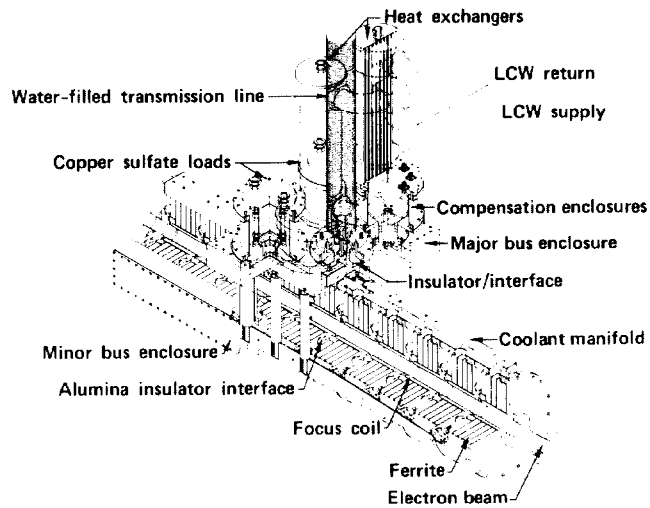

Fig. 5. Ten-cell induction accelerator module on ARC.

6. Summary and Conclusions

The current state of high-repetition rate induction machine technology and the tapered wigglers is sufficient for near-term, high-average-power applications in the microwave and millimeter wavelength regimes. The additional physics demonstrations and developments needed for scaling the technology to shorter wavelengths is verification of the tapered wiggler operation in the optical wavelength regime where "guiding" effects of the radiation are predicted to occur, and the generation and acceleration of very-high-brightness electron beams at multikiloampere current levels. Success in these two developments should open up a wide range of commercial and defense applications of this high-power FEL technology at wavelengths ranging from millimeter to visible wavelengths.

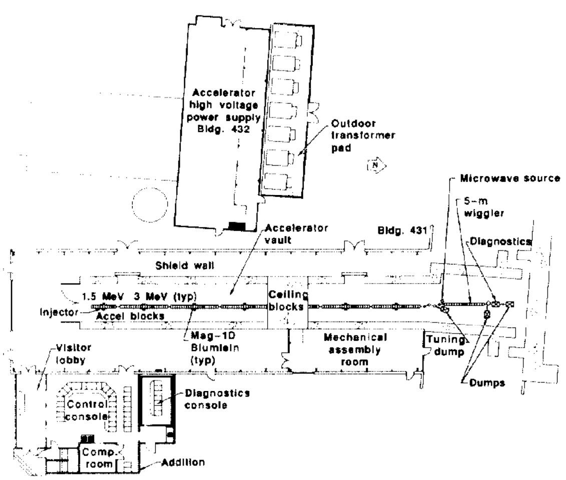

Fig. 6. ETA II.

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