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Overview of FEL Development with Induction Linacs at LLNL

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OVERVIEW OF FEL DEVELOPMENT WITH INDUCTION LINACS AT LLNL*

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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 powers are described.

INTRODUCTION

Induction linacs are capable of producing 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 with the Electron Laser Facility (ELF).[1] Current efforts are focused on extending these results to much shorter wavelengths with 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 the next section. The fundamental physics issues involved in the tapered wiggler operation are described in the following section, with particular emphasis on explaining the requirements of small electron-beam energy spread and high brightness for efficient energy conversion.

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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 (volt-sec) 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 system is the technology 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 the next section.

Radiation from the "pancake bunches" of relativistic electrons is highly peaked in the forward direction 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 $d >> \lambda$, thereby acting like a "forward-fire" phased-array antenna. The overall result is that the FEL gain pattern 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 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.

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

$$\gamma_{\parallel} = \left(\frac{\lambda_w}{2\lambda_s}\right)^{1/2} \pm \delta \ , \tag{1}$$

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

$$\gamma_{\parallel}^2 = \frac{1}{1 - \upsilon_{\parallel}^2/c^2} \ , \tag{2}$$

with $\upsilon_{\parallel}$ 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 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

$$\frac{\Delta\gamma_{\parallel}}{\gamma_{\parallel}} = \frac{b_w \varepsilon_n}{4(1 + a_w^2)} , \tag{3}$$

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 percent) under the constraints of Eq. (1). Obviously if $\upsilon_{\parallel}(\gamma_{\parallel})$ 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[2]; it is called the tapered wiggler.

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 $\gamma_{\parallel}^2$, but operationally it is difficult to build wigglers with the requisite short periods at the downstream end. If one recognizes that

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

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 at LLNL.

ELF was specifically designed to test the tapered wiggler concept. The ELF experiments showed that untapered efficiencies of 5–6% could be increased to 40% by

appropriately tapering the profile of $b_w(z)$, in good agreement with the modeling. 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 are incorporated on the 10.6-μm wavelength PALADIN experiment at ATA.

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 are being addressed on the PALADIN experiments.

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

HIGH BRIGHTNESS AND HIGH AVERAGE POWER

The FEL application using linear induction accelerators places a very high premium on electron beam brightness and on high-average-power operation. A discussion of both these topics has been given in my previous paper on induction linear accelerator technology.

FEL EXPERIMENTS AT LLNL

Our first FEL experiment, completed about two years ago, involved a 4-MeV, high power, pulsed electron beam from our ETA accelerator. The master oscillator was a 35-GHz microwave source coupled to the electron beam at the entrance to the wiggler. Figure 3 shows the 3-m wiggler with the waveguide and external quadrupole magnet coils for guiding the electron beam. Some results from this experiment are given in Fig. 4. The main conclusions from these experiments were that the feasibility of the basic FEL concept described above was confirmed, and that our theoretical models were accurately predicting

performance of these high-gain amplifiers. Further discussions of results from these experiments are given in other papers of this conference.

The extension of FEL amplifier operation to the optical regimes requires higher voltage accelerators, and wigglers of many tens of meters in length. In addition, higher quality electron beams must be generated and transported to the wiggler. In general, all of the technologies became stressed as shorter wavelengths were approached.

The PALADIN experiment, now installed at our Advanced Test Accelerator (ATA), was designed to examine FEL physics at 10.6 μm in a long (25-m) wiggler (see Figs. 5 and 6). This experiment tests the performance of a single-pass wiggler in the regimes of both small and large signal gain. It will give opportunities to validate theoretical models of harmonic generation and will allow examination of the stability of the FEL amplifier against parasitic mechanisms such as sideband instability. We have measured the small signal gain with the first 5 m of the wiggler. At 15 m we have measured the gain of the amplifier and have demonstrated gain guiding. These results will be reported in more depth in another paper in this conference. Currently we are beginning experimentation with the 25-m wiggler with the goal of measuring high gain extraction, optical guiding, and the spatial mode purity of the laser beam. Comparison with theoretical predictions is a key part of the experiment.

We are also planning a microwave FEL experiment on our new ETA-II accelerator, which will ultimately lead to heating of plasma in a tokamak fusion machine at LLNL.

FEL Technology and Fusion Power

The desire to heat plasmas with high power microwaves at millimeter and submillimeter wavelengths may be fulfilled by the free electron laser. The FEL appears ideally suited for this application because it is capable of producing extremely high power and because it has a virtually limitless frequency range. Plasma heating is accomplished by tuning the FEL output frequency to a resonant frequency (cyclotron or twice cyclotron) of the plasma electrons. In a dense plasma, the resonant electrons will absorb the energy of the microwave field and rapidly transfer it to the other plasma particles. Besides having important implications for fusion-power technology, the application of the FEL to electron-cyclotron heating (ECH) may have an impact in other areas of plasma-physics research. The potential for using microwaves to heat plasmas has long been known but has been

thwarted in scaling to higher magnetic fields and higher powers by the technology limits of the microwave-generating (gyrotron) tubes. As the frequency and power-per-unit requirements have grown, the tubes designed to heat plasma have become increasingly difficult and expensive to build. The advantage of FELs is that the high power per unit is an inherent feature of their design.

Experiments will be carried out at LLNL to demonstrate that FEL-generated microwaves can be used for both electron heating and current drive in tokamak plasmas. These experiments will address two issues simultaneously: how pulsing of the high-intensity field affects power absorption, and the physics of the plasma response to high-power microwave heating.

For our planned experiments, we will use the new ETA II facility at LLNL and the Alcator-C tokamak, recently moved to LLNL from the Massachusetts Institute of Technology. The entire endeavor is called the Microwave Tokamak Experiment (MTX). We have begun the tokamak checkout and will begin microwave system checkout during late 1988. Heating experiments should begin in 1989.

A sketch of the facility (Fig. 7) shows the ECH experimental area containing the MTX and the ETA II, which contains the high-energy (7- to 10-MeV) electron-beam accelerator and the FEL wiggler. The electrical and electronic support equipment is not shown.

The MTX will be located just beyond the concrete shield that houses the ETA II. The output end of the FEL will then be situated approximately 19 m from the MTX. Power from the FEL will be transmitted to the tokamak through a quasi-optical, microwave transmission system, which would consist of a network of 0.6-m-diam ducts enclosing four mirrors that focus and direct the FEL microwave beam. The beam will be focused to enter the tokamak vacuum vessel through a narrow (4-cm) port.

Success in these experiments will demonstrate the usefulness of the FEL technology for driving and sustaining reactor plasmas. Good results will also provide a physics base for assessing the FEL's utility in devices for generating fusion power. If this technology fulfills its potential for driving current, controlling instabilities, and improving plasma confinement, ECH could become the method of choice for heating plasmas to ignition and for sustaining steady state plasma current in tokamaks.

FEL Technology and High Power Accelerators

A final application that I wish to discuss is the application of FEL and induction accelerator technology to high power accelerators for high energy physics experiments.

The motivation is for a compact linear accelerator with a high acceleration gradient and an output energy of about 10^{12} eV (1 TeV). Two of these accelerators could eventually be set facing each other and operated simultaneously as a linear particle collider, with a center-of-mass energy during collisions of 2 TeV.

To achieve the necessary acceleration gradients, we are now proceeding with the concept of the two-beam accelerator (TBA), originally proposed by A.M. Sessler in 1982.[3] In concept, the TBA employs a main high-energy-beam linear accelerator driven by a FEL which runs parallel to it and serves as the power source for acceleration. The main accelerator, like that used at the Stanford Linear Accelerator Center (SLAC), is a disk-loaded waveguide powered by microwaves. The innovative feature of the TBA is that it uses an FEL, rather than klystrons or gyrotrons, as the source of the microwaves. With a TBA, power would be tapped off periodically along the FEL wiggler and fed across to the main accelerator. The FEL is designed so that its microwave power increase per unit length is equal to the average power extracted per unit length.

The advantage of employing the FEL—besides its relative simplicity—is its unique, inherent ability to generate economically very high power at very high frequencies. The simplicity of the FEL precludes the need for the thousands of individual microwave generators called for in conventional accelerator designs.

Although the advantage of operating at higher microwave frequencies has long been recognized, there have been no suitable high-power sources at, say, 1-cm wavelengths until the recent development of gyrotrons and FELs.

Gyrotrons are still being developed and may eventually prove to be a practical power source for some linear accelerators. However, their maximum power output at 1-cm wavelength seems likely to remain below 200 MW. Consequently, a 1-TeV machine would require thousands of such power sources, all properly locked in phase. Obviously, such a device would be impractical.

A promising alternative power source for achieving high acceleration gradients at high frequencies is the FEL, which can produce in excess of 1000 MW of average power at 1-cm wavelength. Our current theoretical and experimental work on the TBA is based on the FEL's ability to supply this high microwave power. The TBA (Fig. 8) consists of a

high-gradient, electron-beam-accelerator structure (HGS) periodically coupled to an FEL as a source of high-power microwave energy.

It is interesting that there is an inverse relationship between the basic functional concepts of the FEL and of the HGS: whereas the microwave field of the FEL wiggler obtains its drive power from an electron beam, the electron beam of the HGS obtains its drive power from a microwave field. This relationship has been likened to the operating principle of the transformer, wherein the microwave field is analogous to the transformer's magnetic coupling field.

Although the FEL electron beam loses energy in the process of generating the high-power microwave field, the energy can be replenished by induction accelerator units placed periodically along the length of the FEL wiggler. The exact arrangement of the FEL driver to the high gradient accelerator, whether continuous along its length or modular, is still being evaluated.

Future research on the application of FELs in accelerators will be three pronged. First, we must optimize the design for the FEL's beam reacceleration cavity. Its overall beamline insertion length must probably be held to a few centimeters to avoid seriously degrading the TBA's high average acceleration gradient. Moreover, the microwave power loss in crossing the reacceleration gap should only be a few percent. Initial measurements of gap loss indicate that special focusing or guiding will be required to keep power loss down at an acceptable level.

Second, we must improve the luminosity of the beam. The desired high-energy beam luminosity is difficult to achieve when accelerating single electron bunches. The situation is mitigated by the acceleration of bursts of multiple bunches. This mode of operation has yet to be fully analyzed and optimized.

Third, we must address the issues of phase stability and control, perhaps the largest outstanding TBA design challenge. Analytical studies of the sensitivity of microwave phase to errors in operating parameters are proceeding at Lawrence Berkeley Laboratory. We require a phase-stabilizing scheme that is automatic and nearly instantaneous in response. We are continuing the search for a practical solution.

SUMMARY

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 applications of this high-power FEL technology from millimeter to visible wavelengths.

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3. Sessler, A. M., "The Free Electron Laser as a Power Source for a High-Gradient Accelerating Structure," in Laser Acceleration of Particles (AIP Conf. Proc. No. 91, American Institute of Physics, New York, 1982), pp. 154-159.

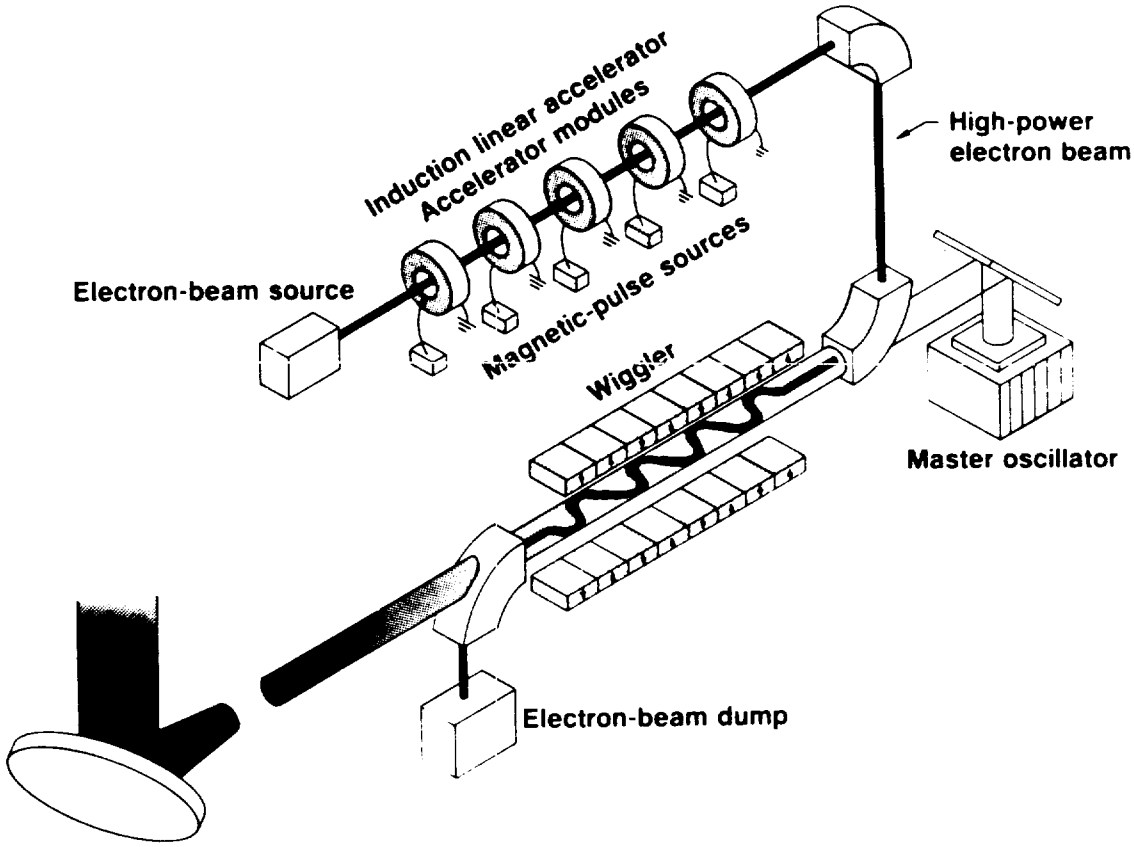
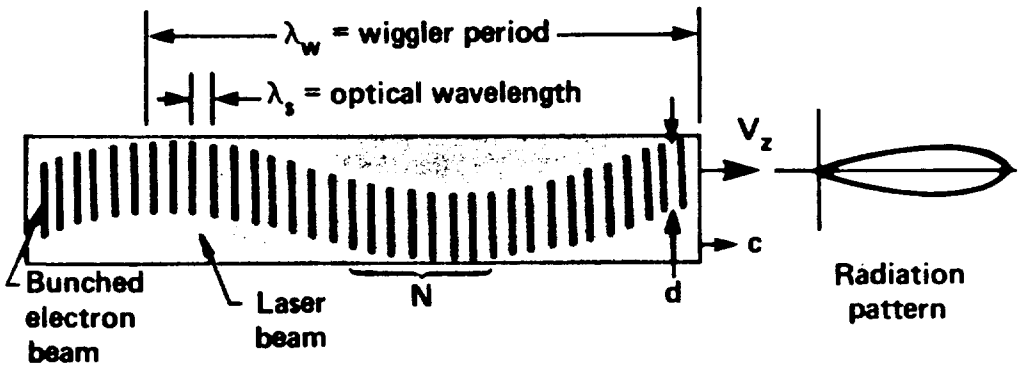


Figure 1. Component technologies for induction linac FEL amplifiers.



- Electron bunches "slip" one optical period per wiggler wavelength relative to light beam

  ⇨ "Slices" of laser and electron beam $N\lambda_s$ long interact independently (N = number of wiggler periods)

- Radiation of bunched beam is strongly peaked in forward direction (like a "phased array" of radiating dipoles of width $d >> \lambda_s$)

Figure 2. Schematic of FEL amplifier operation.

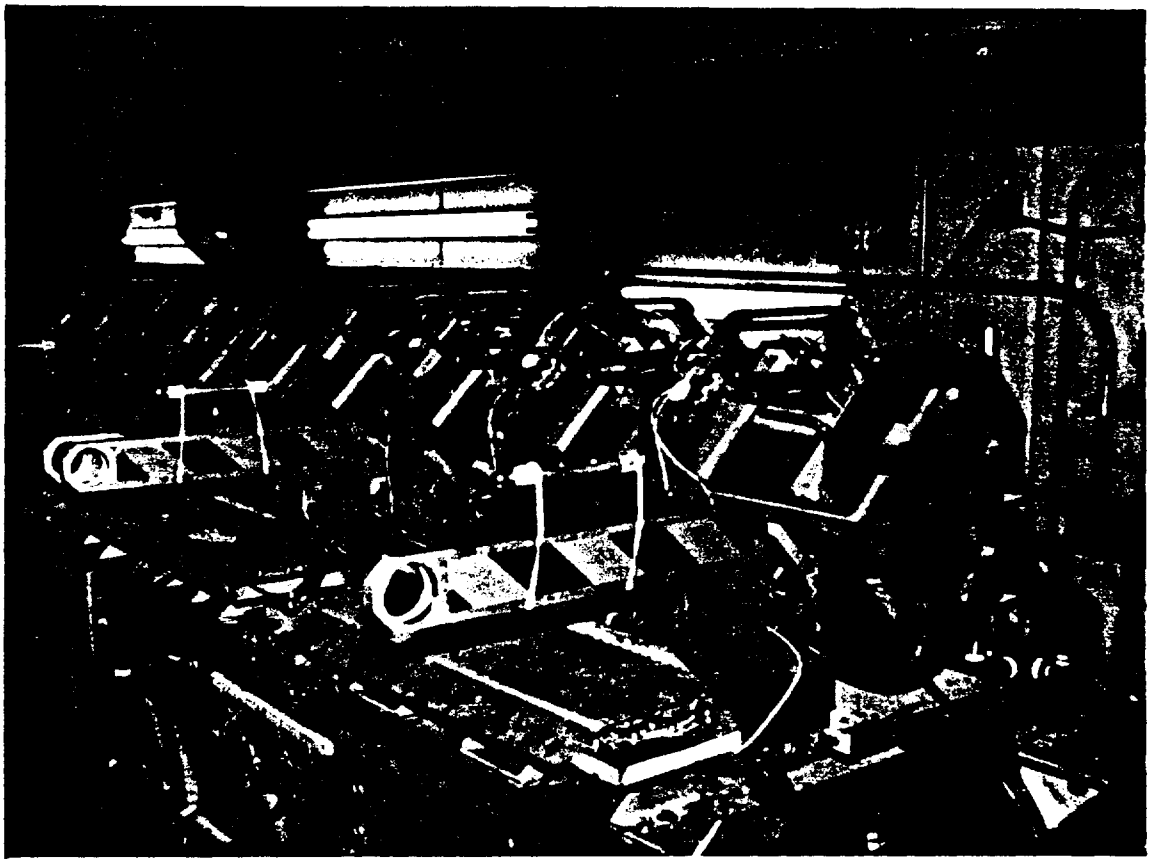


Figure 3. The ELF 3-m wiggler.

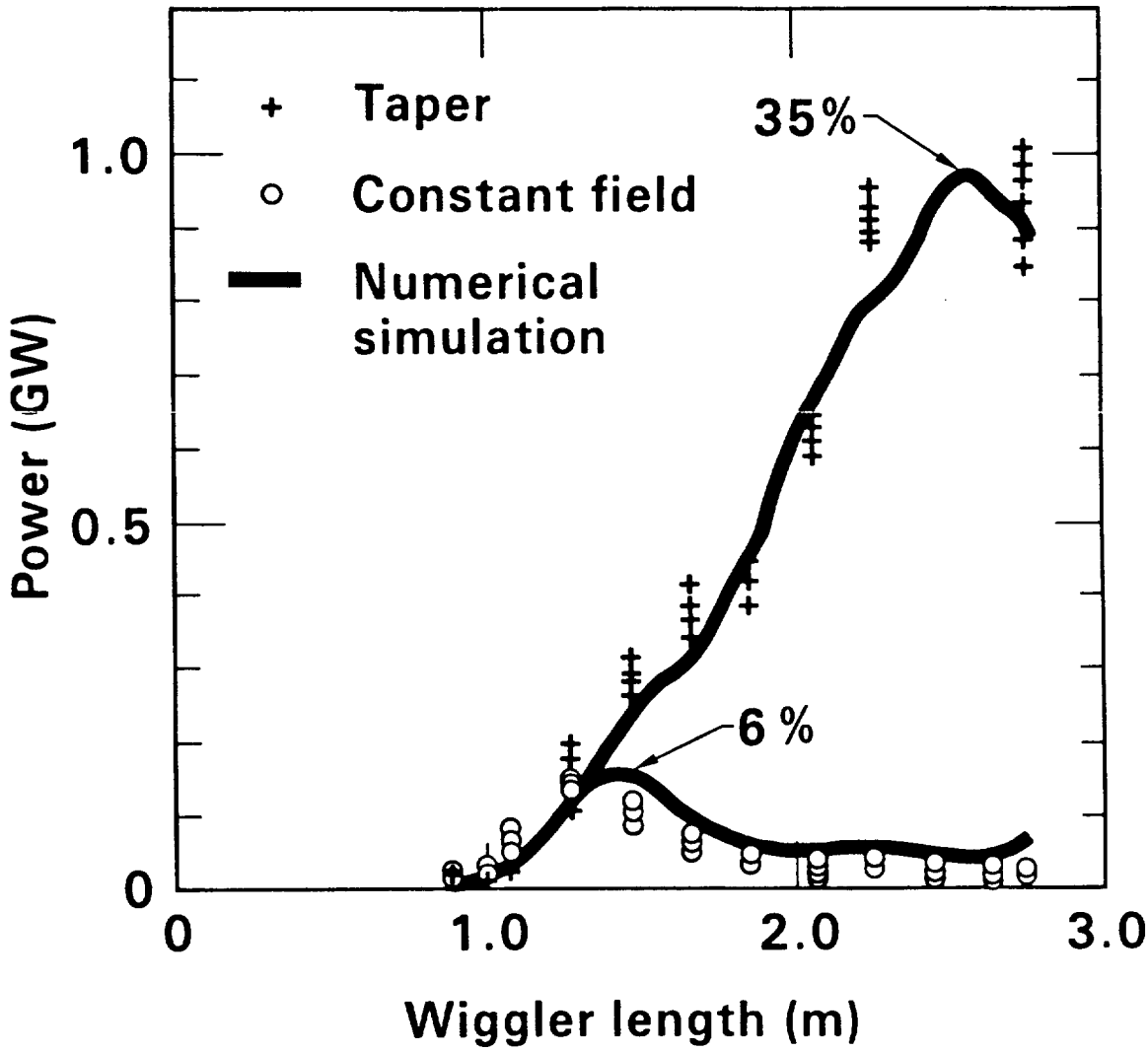


Figure 4. Results from the ELF experiment demonstrate the importance of a tapered wiggler.

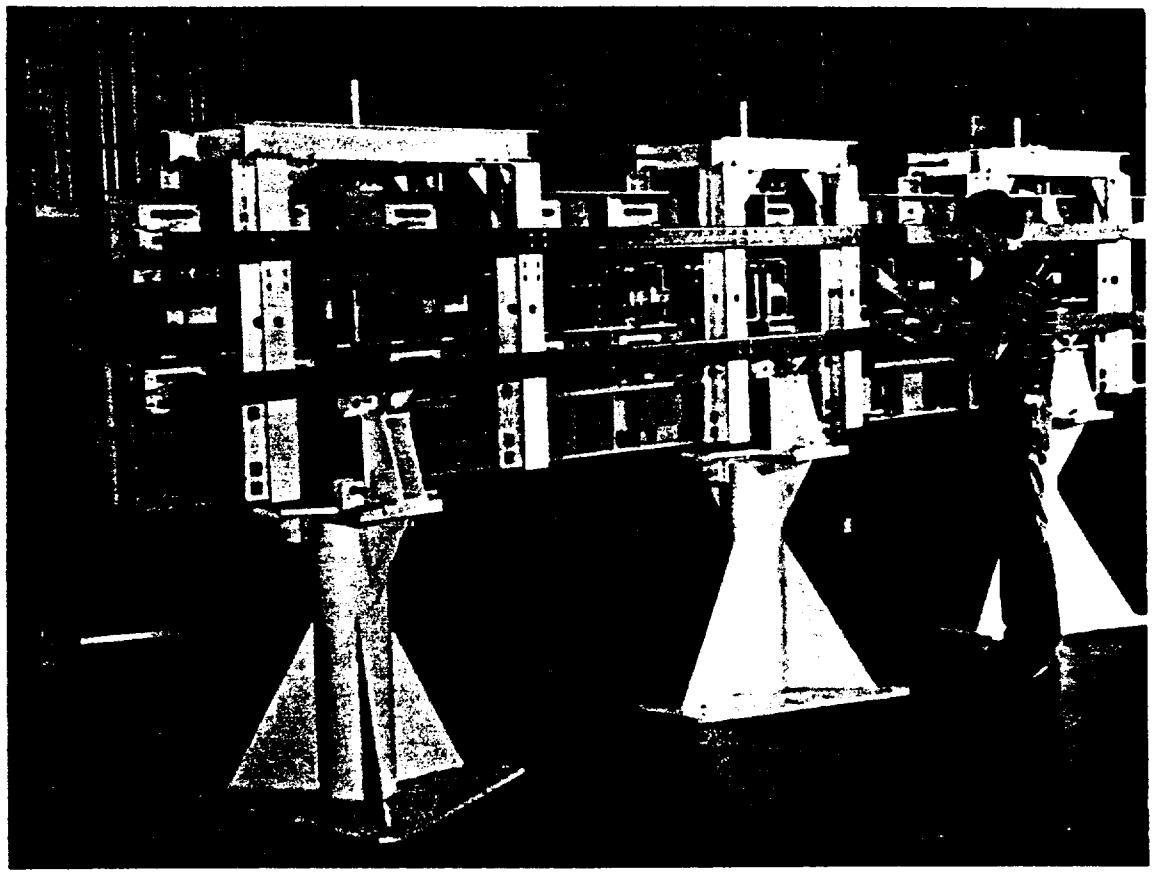


Figure 5. Five-meter section of the PALADIN wiggler.

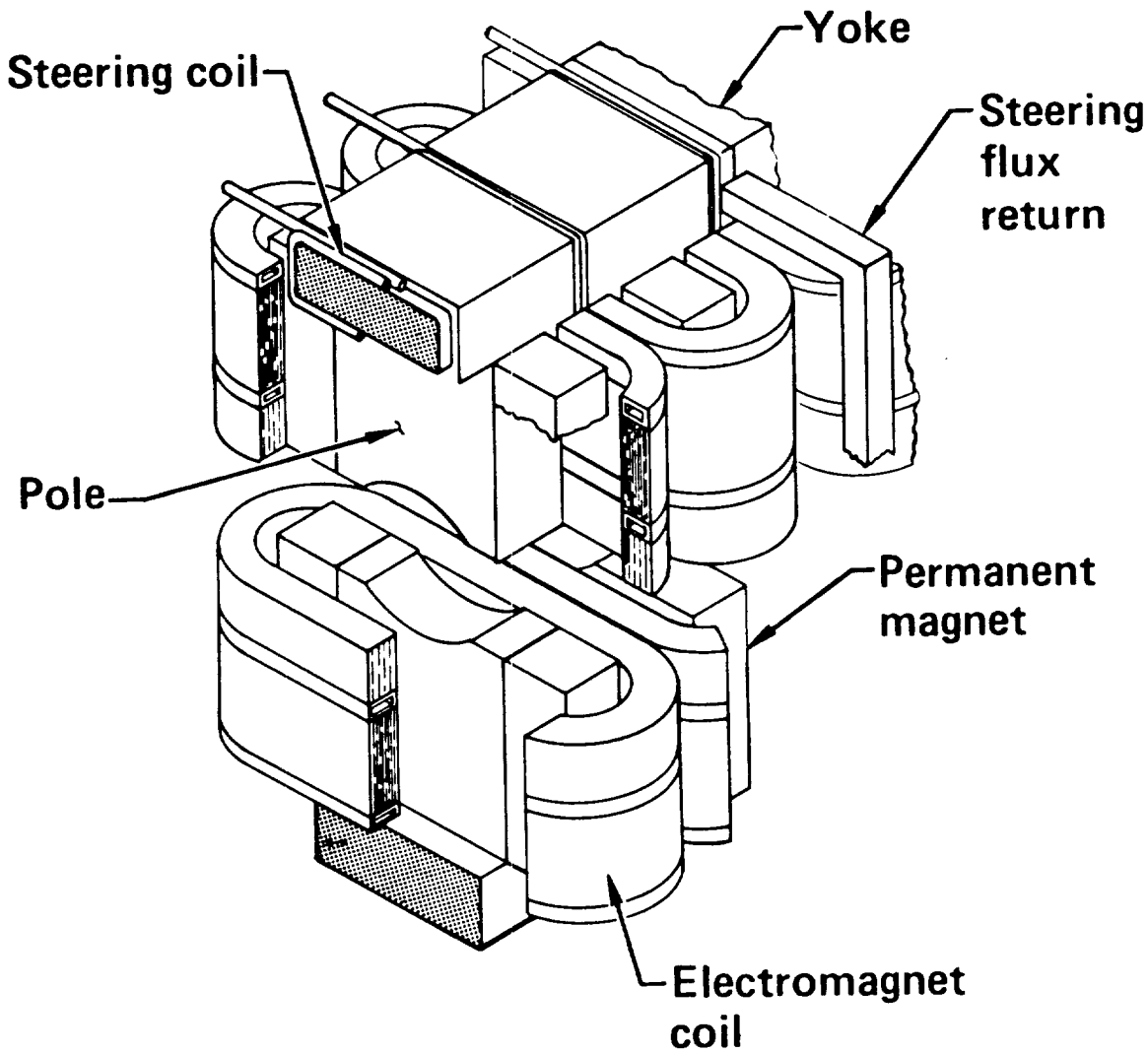


Figure 6. Cutaway of PALADIN wiggler showing poles, main electromagnetic windings, steering coils, and permanent magnet additions to the main pole pieces.

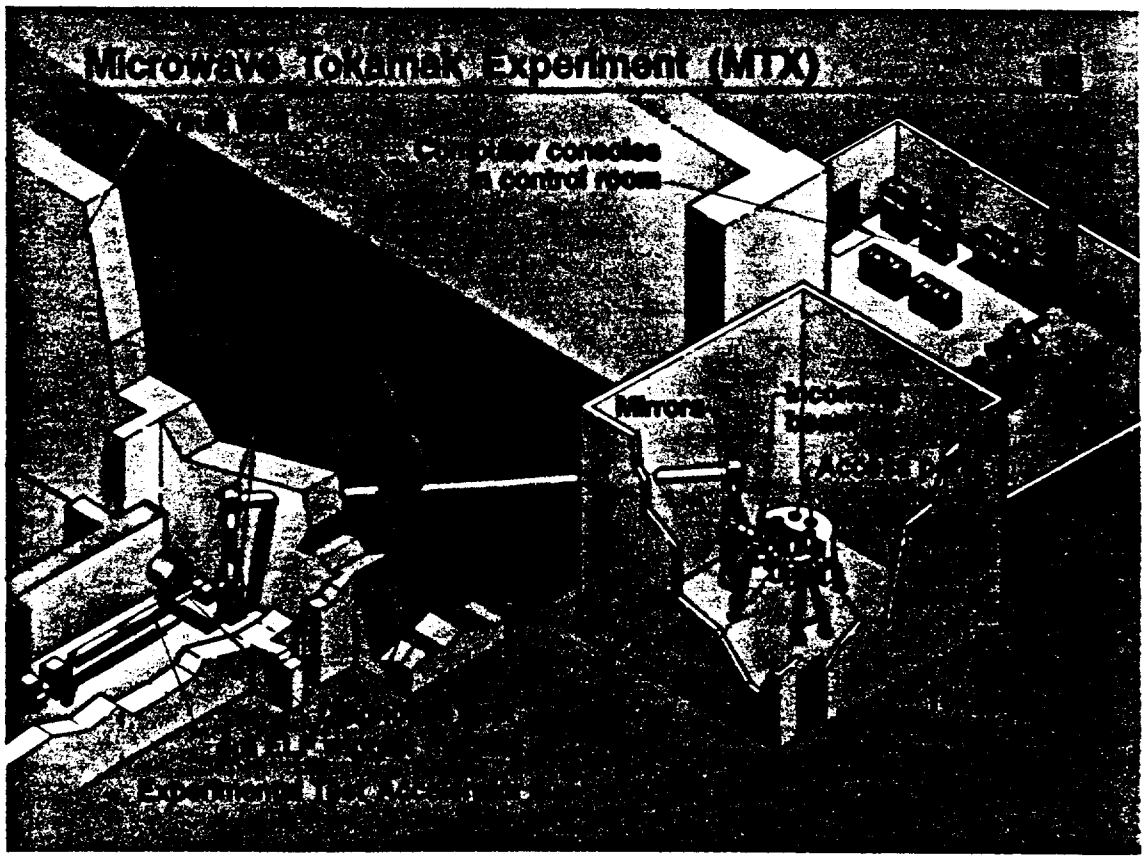


Figure 7. Sketch of the facility for the Microwave Tokamak Experiment (MTX). On the right is the tokamak machine in which the electron-cyclotron heating experiments will be carried out. On the left is the ETA II, containing the electron-beam accelerator and FEL wiggler.

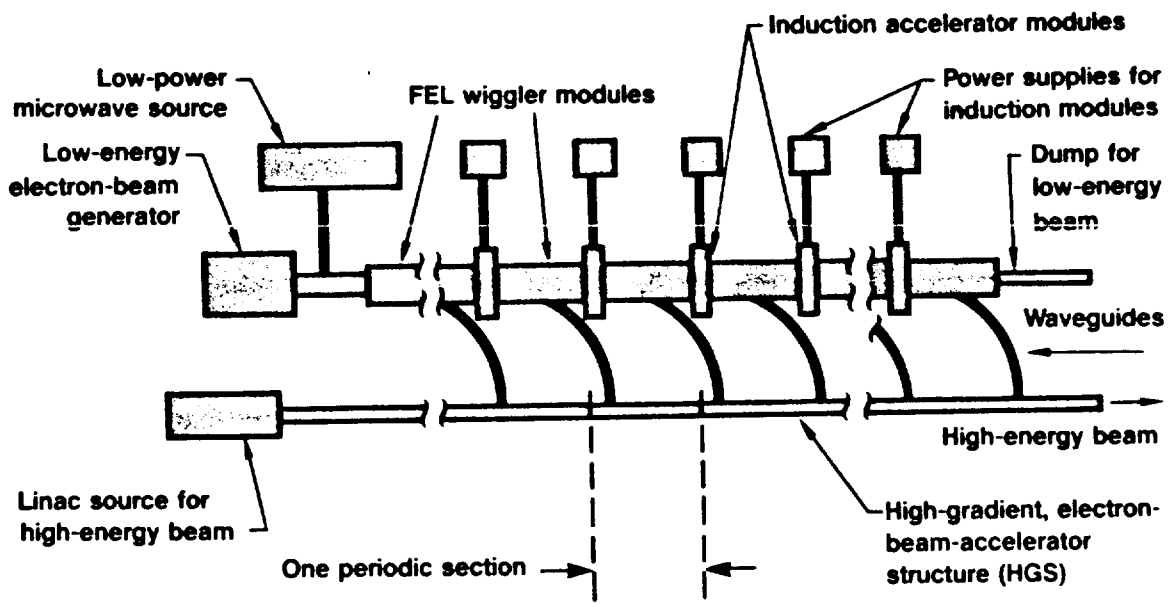


Figure 8. Diagram of the TBA concept. The TBA consists of a high-gradient, electron-beam accelerator structure (HGS) with a FEL wiggler running parallel to it and serving as its microwave-accelerating power source.