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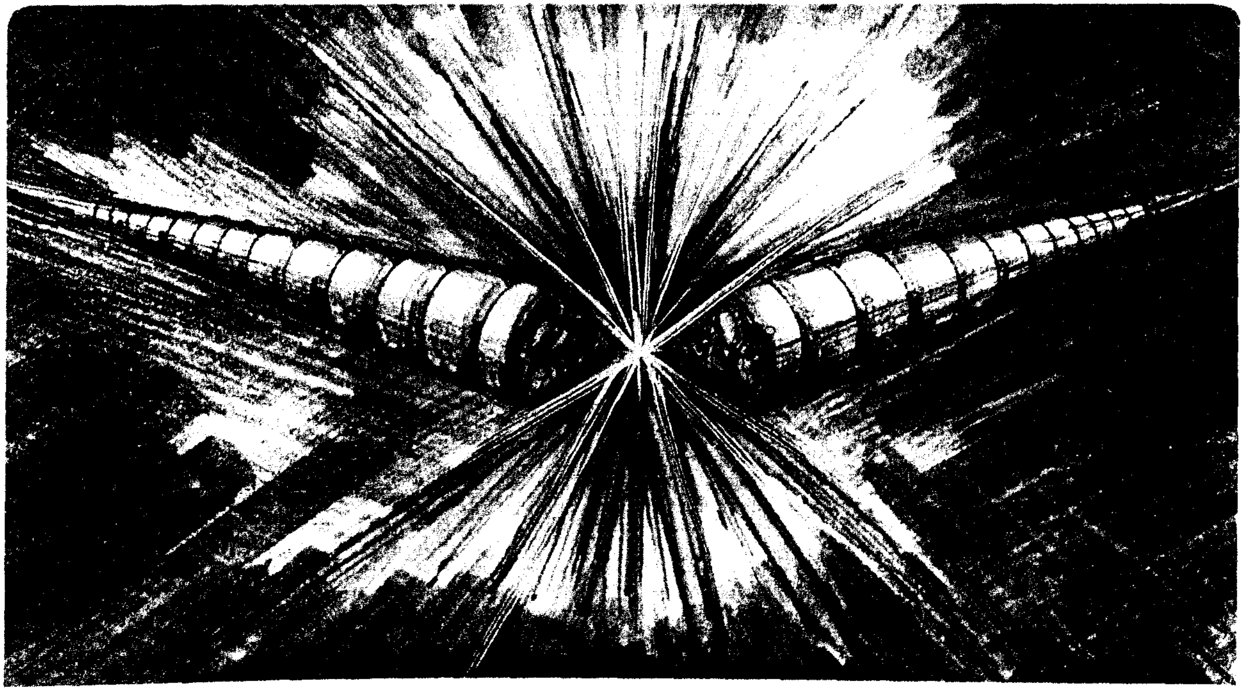

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Free-Electron Lasers: Present Status and Future Prospects[*]

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Free-Electron Lasers: Present Status and Future Prospects*

Kwang-Je Kim and Andrew Sessler

Free-electron lasers as scientific instruments are reviewed. The present status and future prospects are delineated with attention drawn to the size, complexity, availability, and performance capability of this new tool.

The Free-Electron Laser (FEL) was proposed by John Madey in 1970 (1), although earlier work, relevant to the concept, had been performed by Motz (2) and by Phillips (3). Experimental demonstration was achieved by Madey, et. al. in 1975 and 1976 (4). Since that time, FELs of diverse configurations have been operated at several laboratories around the world. At present, FEL development is focused in two directions: in constructing reliable FELs for scientific research and in extending FEL capability to vacuum ultra-violet (VUV) and even shorter wavelengths.

In this article we shall only very briefly review the principles of an FEL, putting emphasis on those aspects that limit performance, after which we shall discuss the applications, present status and future prospects of FELs. Much material that we wish to present is in the form of Tables, and they are an essential part of this article.

The readers of *Science* have had the benefit of a fine review article by Brau (5) in which was described the history, the basic principles, various experiments, and potential applications of FELs. The textbooks on FELs (6) provide even more material, and there have been a number of other review articles (7, 8). In addition, the interested reader may wish to consult the

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Proceedings of the International FEL Conferences (the 12th will be held this year) where much of the original research papers have been published (9).

Principles of the Free-Electron Laser

An FEL produces coherent radiation from a beam of free electrons rather than electrons bound into atoms or molecules, as in a conventional laser. The electrons are passed through a transverse magnetic field alternating in sign along the direction of the electron's motion. The device that produces the periodic magnetic field is known as a wiggler (or sometimes as an undulator). The configuration is shown diagrammatically in Fig. 1, which also shows the resonant optical cavity for the output radiation. The resonance condition involves the electron energy, γ (in units of the electron rest energy mc^2), the magnetic period length, λ_w, the wiggler field strength, B, and the output radiation wavelength, λ. This relation is:

$$\lambda = (\lambda_w/2\gamma^2)\,(1+a_w^2),$$

where the wiggler peak field strength, B, is expressed by

$$a_w = eB\lambda_w/(2^{3/2}\pi mc^2).$$

The tremendous interest in FELs can be seen, immediately, from this resonance condition; namely, the easy tunability of an FEL and the wide range of wavelengths which are available to the FEL. As can be seen from the resonance condition there are three ways to tune an FEL: First, it is possible to design wigglers having a range of wiggler period lengths (usually in the centimeter range). Second, it is easy to generate electron beams having various energies (in γ units, from a fraction to thousands). Third, it is possible to change the wiggler magnetic field.

Thus, unlike a conventional laser, where one is tied to the natural resonance frequency of the atom or molecule, here all frequencies are possible. The electromagnetic spectrum is shown in Fig. 2, where we also show some alternative sources of radiation. One notes that sources are lacking both in the infrared region ($1\ \mu\text{m} \leq \lambda \leq 1$ mm), and in the ultraviolet and shorter wavelength region ($\lambda \leq 1000$ Å). Free electron lasers could presumably fill these gaps. In Fig. 3 we show the performance of FELs to date; one can see that the features of operation in different wavelength ranges and tunability have already been demonstrated.

The wiggler can be constructed from either electromagnets or permanent magnets. Attention must be given to the field quality and alignment of the wiggler. The development of high-field, short period wigglers, using permanent magnets, has been an important factor in constructing efficient FELs. The magnetic field of a permanent magnet wiggler can be easily changed by changing the wiggler gap.

An FEL can be operated either as an oscillator, as we show in Fig. 1 where an optical cavity is indicated, or as an amplifier. Most FELs are operated in the oscillator mode, and attention must be given to mirror properties. In an amplifier mode, the gain in a single traverse needs to be significant and this requires an intense electron beam. (In an oscillator, the gain per pass only needs to be larger than the loss per pass.)

In the amplifier mode, since no mirrors are involved, operation can be obtained in short wavelength ranges where high reflectivity mirrors are difficult to construct. Either an input signal may be used, which can readily be done for longer wavelengths, or amplification can be made to grow from noise by means of self-amplification of spontaneous radiation (SASE). In the short wavelength range, where even low-power input signals are not available, an FEL must rely upon growth from noise.

As an electron moves down the wiggler of an FEL it loses energy to the growing electromagnetic wave and, consequently, no longer satisfies the resonance condition. As a result, the FEL stops working; i.e. "reaches saturation". This can be avoided by varying the wiggler field, B, to match the changing resonance condition. With this so-called "tapering", the FEL continues to operate even when the wiggler is very long. Tapering is very important for high gain amplifier operation.

An FEL "works well" provided certain conditions on the quality of the electron beam are satisfied. In the past, essentially all the difficulties with FELs have not been due either to technological problems in the FEL or to theoretical problems concerning FEL operation, but rather that the electron beam was not of sufficient quality, i.e. did not satisfy the conditions required for operation of an FEL. As the technology of electron beams improves, one can expect to see ever more powerful FELs; i.e., FELs that span an even larger range of wavelengths and produce even more power.

Roughly, beam quality is described by two quantities: beam energy spread $\Delta\gamma/\gamma$ and beam emittance. The energy spread is a measure of longitudinal spread, while the emittance is a measure of the transverse spread. The emittance, ε, is given by the product of beam radius, a, and beam angular divergence, θ, so that $\varepsilon = a\theta$.

What are the conditions on electron beam quality? An optical beam has an emittance of order λ, where λ is the wavelength. Thus it is required to have the electron beam emittance matched to the optical beam; i.e. $\varepsilon \leq \lambda$. The FEL gain bandwidth is $1/N$, where N is the number of periods in the wiggler. It is necessary to have the energy spread less than gain bandwidth; i.e. $(\Delta\gamma/\gamma) \leq 1/N$.

Besides these two conditions on beam quality, there is a condition on beam current. That condition is related to the required gain and therefore depends upon the mode of operation of the FEL. We shall not go into details here, but roughly the requirement is a few amperes for an oscillator and a few hundred amperes for an amplifier.

Applications

There are many applications envisioned for FELs. (We say "envisioned" for, so far, there have been very few actual uses of FELs.) A number of conferences have been devoted to the subject (10). In Table 1 we list some of these potential applications.

Microwave

High power from an FEL operating in the microwave range has already been demonstrated. Thus applications requiring this capability, such as plasma heating in tokamaks or acceleration of particles in conventional linacs, are near at hand. For plasma heating the primary physics issue is the plasma response to the high peak power of an FEL (which necessarily brings in non-linear effects that may be advantageous or not) in contrast with conventional (almost DC) gyrotrons. There are, also, economic considerations.

In the accelerator application, FELs become the microwave sources and therefore make possible operation in the high frequency range (up to (say) 30 GHz vs 3 GHz in the large accelerator at Stanford) where conventional klystrons are no longer effective. The primary issue is economic and to this end two-beam accelerators have been developed. They employ a drive beam for powering the FEL and a second beam which is accelerated to high energy. Two-beam accelerators plan to increase efficiency (and hence reduce operating cost) while tolerating a larger capital cost, but because they have various novel features they bring in new physics issues which are, only now, being studied.

Infra-Red

Many of these applications can be expected rather soon; i.e., they require radiation in the infra-red (IR) (which is relatively easy to come by), but they do not require high power. Nevertheless these applications require facilities which take account of the user needs in such things as stability, line width, reliability and ease of tuning, etc. Radiation from an IR FEL can be used to manipulate molecular vibrations and chemical reactions in both the condensed and the gas phases. The IR pulses will open up new studies on intra molecular vibrational energy transfer using the technique of infrared multiphoton excitation and dissociation, a technique so far limited to the molecular species that can be excited by CO_2 lasers. With broadly tunable IR FELs, the technique can be extended to practically all molecular species. The new studies will provide valuable information on, for example, the combustion phenomena. High average power IR FELs would ultimately allow materials to be synthesized from across a wide range of the periodic table. The pump-probe type experiments involving an IR FEL and a second light source, which can be another FEL, a conventional laser or a synchrotron light source, will allow quantitative studies of many surface phenomena, such as time dependent redistribution of surface molecules, diffusion, desorption, etc. Measurement of the band gap of the high T_c superconductor will be possible because of the high intensity of the IR FEL radiation.

Most military and medical applications require high power at short wavelengths (about 1 μm). This level of operation has not yet been achieved by FELs and thus these applications still lie in the future.

Short Wavelengths

The applications in the UV and the X-Ray range are most attractive and are driving the FEL physicist to learn how to operate at very short wavelengths. For example, there is great desire to reach the "water window", between 24 Å and 44 Å, where biological materials can be studied in their natural aqueous environment. Also, there is great interest in obtaining sufficient power at short wavelengths as to be able to do projection lithography and material processing, and in obtaining sufficient spatial coherence for holography, and in obtaining sufficiently narrow bandwidth and intensity for probing the fine details of chemical dynamics of dilute samples, etc. Some capabilities, in coherence and in power, in the short wavelength region, will be available soon with the completion of the advanced synchrotron radiation facilities under construction at several laboratories around the world (see Fig. 2) (11). Experience in dealing with intense short wavelength radiation with these sources will provide a base for the more challenging experiments possible with the more intense and coherent FEL sources.

Present Status

That there is considerable interest in the FEL is obvious and need not be said. Just a list of world-wide activities speaks strongly, and in Table 2 we present such a list. This compendium lists on-going projects, past projects, and future projects. The purpose of the Table is to give a feeling for the range of activities and the diversity of the activities.

Notice that the projects employ just about every kind of electron accelerator known to man. That is in part a result of history (what an institute happens to have and what it has expertise in), and in part because it is not yet clear what is the most suitable accelerator for a particular kind of FEL.

Going beyond a mere list of projects, we have selected a few representative projects and presented more information about them in Table 3. These are all operating FELs, so the performance characteristics are very "real". We have listed the wavelength range, the line width of the radiation, the pulse structure, the energy per pulse, and the average power. The reader can compare this performance with that of other sources, and consider experiments now possible that previously were not so. Suffice it to say that these projects are the base upon which world-wide enthusiasm for new FEL projects has been built.

In Fig. 4 we show the FEL undulator installed on Super-ACO at Orsay. The reader should note that the installation is large, complicated, and expensive. True, this particular facility is a bit larger than those FEL facilities in the infra-red (the Orsay Facility is primarily a synchrotron radiation facility serving many users), but the general impression is correctly given, FEL facilities are not small and inexpensive and it seems unlikely that they will ever become "table top" and hence readily available to any researcher, or, even, available in every university or institute. Much more likely is the development of regional, or even national, centers.

Future Prospect

In the future FELs will be developed in two separate directions: In the infrared region, where the technologies for the accelerator and optical cavities are available, the emphasis will be on constructing user facilities. In the short wavelength region, the emphasis will be on the development of technology.

IR FEL User Facilities

IR FELs have been built and operated; but these first devices were oriented towards learning about FELs rather than towards serving a community of users. The challenge in the future will be to build an FEL satisfying a unique set of criteria required for a user facility. We list parameters of four representative new facilities in Table 4. The first three facilities in this Table are under construction. The last one is in the proposal stage, but is listed here as it is a representative of the present state of the art and shows what can be expected. All of these facilities are planned to be operated rather reliably, in a stable manner, and for a very large percentage of scheduled operating time.

An important criteria for an FEL user facility is the stability of the FEL output, in wavelength, in intensity, and in direction. Thus the choice of the accelerator system and design must be made with the view of ensuring the required stability. The jitter in electron beam parameters, such as the electron beam energy, charge, timing, etc., needs to be tightly controlled by employing feed-back and feed-forward correction. Thus, for example, the fluctuation in the electron beam energy for the CDF will be reduced to less than 0.05%.

Another important criteria is the ease of wavelength coverage and tuning; the facility must provide a wide wavelength coverage with minimum interruptions to the users. It is more or less straightforward to change the electron energy or the wiggler gap. It is less straightforward to design a broad band optical system which includes the optical cavity, output coupling and beam transport from the FEL to the experimental station. Work in this direction is just beginning and can be expected to advance significantly in the future.

FELs for 1000 Å or Shorter Wavelengths

The short wavelength record in FEL is 2400 Å obtained at Novosibirsk. Realizing FELs for short wavelengths is difficult because the electron beam requirements are more demanding: higher energy, higher current, smaller emittance and smaller energy spread. Also, high reflectivity mirrors suitable for optical cavity are currently not available. In spite of these difficulties, several laboratories are engaging in research for the development of short wavelength FELs because the scientific payoffs are great (16, 17).

Among different accelerators, electron storage rings appear to be the most promising source of electron beams for short wavelength FELs. This is because of the unique radiation damping mechanism that improves, and maintains, beam quality in the storage ring. The accelerator community has gained considerable experience recently in the art of building high brightness electron storage rings in connection with the advanced light source projects at several places around the world. The drawbacks of the storage ring-based FELs are that the storage rings are big and expensive and that the average output power tends to be limited because the damping is a slow process.

Another approach is to use RF linacs. In that case, it is necessary to start out with a good emittance beam since there is no damping mechanism. The recent development of laser driven RF photo-cathodes (18) appears to make possible the generation of such low emittance, yet intense, beams. It is upon this new technology that the linac FELs, for very short wavelengths, are based. The linac technology benefits from high energy physics linear collider projects.

Multifacet mirrors and multilayer mirrors are currently under development for use in short wavelength FELs. The use of mirrors can be entirely avoided if FELs are run in the amplifier mode. As the input radiation, if available at all, is usually quite weak in the short wavelength region, the FEL in the amplifier mode is inherently a high-gain device. In the case of extreme high gain, with a gain of one million or larger, the FEL can amplify the initial noise signal (the undulator radiation) to intense, coherent radiation. While operation in this (SASE) regime requires neither mirrors nor coherent input signals, the requirements on the electron beam qualities and the wiggler construction are very demanding.

Considerable effort is going into the development of short wavelength undulators. This development is important for short wavelength FELs as the smaller λ_w is made, less energetic are the electrons required for a given optical wavelength. At present, undulators with wavelengths of (about) $\lambda_w = 1$ cm are being developed employing either permanent magnets, superconducting magnets, or electromagnetic (iron) magnets.

Laboratory and theoretical work is being undertaken on the development of even shorter wavelength ($\lambda_w \approx$ mm) undulators ("micro-undulators"), gas-loaded FELs, plasma-loaded FELs, and two-stage FELs. All of this work is motivated by the desire to reach short wavelengths in an economic and reliable manner. However, none of these developments have yet reached the stage of being incorporated into projects.

In Table 5 we list the parameters of some short wavelength FEL projects. The Duke facility is being constructed, LANL is building linacs for their facility, the other two are in a very preliminary stage. The LBL facility employs an amplifier, rather than an oscillator, so as to avoid the use of mirrors. The consequence is that the storage ring peak current must be very large and the FEL wiggler very long and of high field. The last requires a small gap, so small that the wiggler must be put into a special by-pass section of the storage ring (so as to avoid drastic reduction of the electron beam lifetime); the electron beam is switched into the by-pass once per damping time.

Conclusions

It has been two decades since a free-electron laser (FEL) was first conceived. During that time many different FELs have been built, operated, and analyzed, and as a result the understanding of FELs has been greatly advanced. Only a few experiments have so far been done using the photons from an FEL, but a number of "user facilities" (in the infra-red) are now under construction and the next decade should witness a flowering of experiments using the unique capabilities of FELs. In addition, the FEL appears to be capable of producing UV, VUV, and even X-ray, radiation. Work on this frontier is on-going, but no "user facilities" can be expected in this decade, perhaps in the decade beyond.

REFERENCES AND NOTES

1. J.M. J. Madey, J. Appl. Phys. **42**, 1906 (1971).
2. H. Motz, J. Appl. Phys. **22**, 527 (1951).
3. R.M. Phillips, IRE Trans. Electron Devices **7**, 231 (1960).
4. L.R. Elias et al, Phys. Rev. Lett. **36**, 717 (1976); D.A.G. Deacon et al, Phys. Rev. Lett. **38**, 892 (1977).
5. C. Brau, "Free-Electron Lasers", Science **239**, 115 (1988).
6. T. Marshall, "Free-Electron Lasers", MacMillan (1985); C Brau, "Free-Electron Lasers", Academic Press (1990).
7. W.B. Colson and A.M. Sessler, "Free-Electron Lasers", Ann. Rev. Nucl. Sci. **35**, 25 (1985); A.M. Sessler and D. Vaughan, American Scientist **75**, 34 (1987); B.E. Newnam, Editor, "Free-Electron Lasers", Critical Reviews of Optical Science and Technology, The International Society for Optical Engineering, SPIE **738** (1987); H.P. Freund and R.K. Parker, "Free-Electron Lasers", Scientific American **260**, 84 (1989).
8. J.M. Ortega, "Free Electron Laser and Harmonic Generation", Synchrotron Radiation News **2**, #2, 18 (1989); **2**, #3, 21 (1989); **3**, #1, 24 (1990).
9. Proceedings of the 10th International Free-Electron Laser Conference, Jerusalem, August 29-Sept 2, 1988, Nucl. Instr. and Methods in Phys. Res. **A285** Nos. 1, 2 (1989) and previous conferences referenced therein.

10. Proceedings of the Workshop on Applications of Free-Electron Lasers, Castelgandolfo, Sept. 1984, Nucl. Instr. and Methods in Phys. Res. **A239** No. 3, (1985); Free-Electron Laser Applications in the Ultraviolet, 1988 Technical Digest Series, Vol. 4, Optical Society of America, Washington, DC. 1988; Free-Electron Lasers and Applications, D. Prosnitz, Editor, Proc. SPIE 1227, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1990.

11. D. Attwood, K. Halbach and K.-J. Kim, "Tunable Coherent X-Rays", Science **228**, 1265 (1985).

12. P.W. Van Amersfoot, et. al., The Felix Project Status Report, April 1988, Rijnhuizen Report 88-176 (1988).

13. NBS-NRL Free-Electron Laser Conceptual Report, S. Penner, Editor, NBS-NRL FEL Collaboration, March 1988.

14. J.C. Bourdon et. al., "CLIO: Free-Electron Laser in Orsay", Proc. of 1988 European Particle Accelerator Conference, Rome, World Scientific Pub. Co., 314 (1989).

15. Conceptual Design Report, Combustion Dynamics Facility/LBL, Lawrence Berkeley Laboratory Report PUB-5250 (1990).

16. J.M.J. Madey and C. Pellegrini, Editors, *Free Electron Generation of Extreme Ultraviolet Coherent Radiation*, AIP Conference Proceedings No. 118, American Institute of Physics, New York (1984).

17. B.E. Newnam, "Extension of FELs into the Extreme Ultraviolet", Ref.1, p. 155; C. Pellegrini, "Progress Towards a Soft X-Ray FEL", Nucl. Instr. and Methods in Phys. Res. **A272**, 364 (1988).

18. J. S. Fraser, R.L. Sheffield, E.R. Gray, and P.M. Giles, "Photocathodes in Accelerator Applications", Proc. of the 1987 IEEE Particle Accelerator Conference, IEEE 87CH2387-9,1705 (1987).

19. B. Newnam, "XUV Free-Electron Laser Developments at Los Alamos", Proc. of 1988 Linac Conference, CEBAF-89-001, 290 (1989).

20. J.E. La Sala, D.A.G. Deacon, J.M.J. Madey, "Performance of an XUV Free-Electron Laser Oscillator at the Stanford Storage Ring", Nucl. Instr. and Methods in Phys. Res. **A250**, 262 (1986).

21. J. Bisognano, et. al., "Feasibility Study of a Storage Ring for a High-Power XUV Free-Electron Laser", Particle Accelerators **18**, 223 (1986).

22. R.B. Palmer and J.C. Gallado, private communication.

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Table 1. FEL Applications

1. Condensed Matter Studies
   - Surface science (IR)
   - Semiconductors (IR)
   - Superconductors (IR)
   - Magnetic properties (IR, soft x-rays)
2. Non Linear Plasma Studies
   - Heating (microwave)
   - Current drive in tokamaks (microwave)
3. Non-Linear QED Studies (1μm or 10 μm)
4. Non-Linear Optics and Non-Linear Microwaves
5. Inertial Fusion (~ 1/2 μm)
6. Chemistry
   - Molecular excitations (IR)
   - Dynamic reactions (1-10 μm)
   - Crossed photon-molecular beams (1000-2000 Å)
7. Biology
   - Microscopy (40 Å)
   - DNA studies (5 Å)
   - Cell response (IR)
8. Medicine
   - Surgery (1-10 μm)
   - Photo-reactions (IR)
9. Accelerators
   - Inverse Free Electron Lasers
   - Two Beam Accelerators (1-10 mm)
10. Chemical production (VUV)
    - Fixing polymers
    - Making drugs
11. Isotope separation (IR)
12. Lithography (10 Å)
13. Military uses (IR, Visible)

Table 2. World-Wide FEL Projects

China	Shanghai (Diode, RF Linac)
	IAE, Beijing (RF Linac)
	IHEP, Beijing (RF Linac)
	Chengdu (Induction Linac)
England	Glasgow (RF Linac) (project terminated)
France	Orsay, ACO (Storage Ring) (project completed)
	Orsay, Super ACO (Storage Ring)
	Orsay, CLIO (RF Linac)
	Bruyères (RF Linac)
	Palaiseau (Diode)
	Lille/Dijon (Electrostatic)*
	Bordeaux (Induction Linac)
Germany	KFI, Darmstadt (Superconducting)
	Dortmund DELTA (Storage Ring)*
Israel	Technion (Diode)
	Weizmann (Electrostatic)
Italy	ENEA, Frascati (Microtron)
	INFN, Frascati, ARES (Superconducting RF Linac)
	Milan, ELFA (Superconducting Linac)*
	Padua (Electrostatic)*
Japan	JAERI (Superconducting RF Linac)
	Narashimo (Microtron)
	Mitsubishi (RF Linac)
	Univ. of Tokyo (RF Linac, Storage Ring)
	Osaka (Induction Linac, Diode)
	ISIR (RF Linac)
	ETL (Storage Ring)
Netherlands	FOM, Rijnhuizen FELIX (RF Linac)
	Twente (Microtron)
USA	Stanford, SCA (Superconducting RF Linac)
	Stanford, Mark III (RF Linac) (project completed)
	Duke (RF Linac)
	Duke (Storage Ring)
	Los Alamos (RF Linac)
	Boeing (RF Linac)
	Santa Barbara (Electrostatic)
	NRL (Diode) (project completed), (Induction Linac)
	Columbia (Diode)
	Livermore, ELF, Paladin (Induction Linac) (project completed), MTX (Induction Linac)
	NIST-NRL (Microtron)
	Vanderbilt (RF Linac)
	Florida, CREOL (Electrostatic)*
	Brookhaven (Storage Ring) (project terminated), (RF Linac)
	MIT (Diode, Induction Linac)
	Hughes (Diode)
	LBL (RF Linac)*
	UCLA (RF Linac)*
	Bell Labs (Microtron)
USSR	INP, Novosibirsk (Storage Ring)
	Erevan (Microtron)

*Proposed

Table 3. Representative Operating FELs

	LANL	Stanford Mark III	UCSB	Stanford SCA	Novosibirsk	Orsay
Accelerator	RF Linac (standing wave)	RF Linac (traveling wave)	DC	Super Conducting Linac	Storage Ring	Storage Ring
Electron Energy	23 MeV	45 MeV	3 MeV	66 and 115 Mev	350 MeV	150-240 MeV
Wavelength Range	10-45 μm	2-8 μm	130-400 μm	0.5-3.0 μm	2400 Å-6900 Å	5700 Å-6400Å
Bandwidth ($\frac{\Delta\lambda}{\lambda}$)	0.3%	0.5%	0.1%*	0.1%	0.01%	0.01%
Micro-Pulse Duration	8 psec	1-2 psec	3 μsec	2-4 psec	75 psec	<300 psec
Rep Rate			50 Hz		8 Mhz	27 MHz
Micropulse	22 MHz	2.8 GHz	–	12 MHz	–	–
Macropulse	1 Hz	15 Hz	–	10-20 Hz	–	–
Micropulse Energy	200 μJ	5-7 μJ	4.5 mJ	1-5 μJ	1-100 nJ	2-5 nJ
Average Output Power	1 W	3 W	0.23 W	10 W	6 mW	3 mW

* Including jitter

Table 4. Parameters of Some Planned Facilities (Infra-red)

	Felix(12)	NIST-NRL(13)	CLIO(14)	CDF(15)
Accelerator	RF Linac	Microtron	RF Linac	RF Linac
Electron Energy	15-45 MeV	185 MeV	30-70 MeV	56 MeV
Wavelength Range	5-160 µm	0.2-10 µm	2-20 µm	3-50 µm
Micropulse Duration	3 psec	3 psec	10-15 psec	10 psec
Macropulse Duration	20 µsec	–	10 µsec	100 µsec
Rep Rate		74 MHz		
Micropulse	1000 MHz	–	30-500 MHz	37 MHz
Macropulse	10 Hz	–	50 Hz	60 Hz
Micropulse Energy	25 µJ	0.1-3.0 µJ	100 µJ	200 µJ
Average Output Power	5 W	25-200 W	10-100 W	20 W

Table 5. Parameters for Representative Short Wavelength FEL Projects

	LANL(19)	Duke(20)	LBL(21)	BNL(22)
Accelerator	RF Linac	Storage Ring	Storage Ring	Superconducting Linac
Electron Energy	100-500 MeV	800-1000 MeV	750 MeV	250 MeV
FEL Type	Oscillator	Oscillator	Amplifier	Amplifier
Wavelength	10-4000 Å	50-4000 Å	400 Å	1000-3000 Å
Micropulse Duration	10-30 psec	300 psec	100 psec	5 psec
Rep Rate		3 MHz	10 Hz	3-10 kHz
Micropulse	10-100 MHz	–	–	–
Macropulse	30 Hz	–	–	–
Peak Output Power	1-10 MW	10 kW	50 MW	300 MW
Average Output Power	1-10 W	10 W	50 mW	15 W

FIGURE CAPTIONS

Fig.1. A schematic diagram of a free-electron laser. A beam of electrons is generated in the electron accelerator and then passed through a region of alternating direction magnetic field (wiggler). Coherent light is generated and contained in an optical cavity defined by the mirrors. Needless to say concern must be given to generating, focusing and transporting the electron beam as well as to proper treatment of the light beam.

Fig. 2. FELs have already provided tunable, coherent radiation in the IR and UV spectral ranges. The diagram shows the power, and range, of some other sources of radiation; conventional microwave sources (tubes, klystrons, gyrotrons, etc.), lasers, plasma lasers (indicated by ʘ), undulators on third generation synchrotron radiation facilities. One can see that there are wide ranges of the spectrum where there is need for the FEL. Possible FEL performance is indicated by the cross-hatched region.

Fig. 3. Achieved FEL performance as a function of wavelength. One notes the wide range of wavelengths in which FELs have been operated, as well as the wide tunability ranges realized.

Fig. 4. The FEL in the Super ACO Storage Ring. One notes that the facility is complicated and represents a considerable investment. That is generally true of FELs; they are not cheap and it seems most unlikely that they will ever become table-top in size like ordinary lasers.

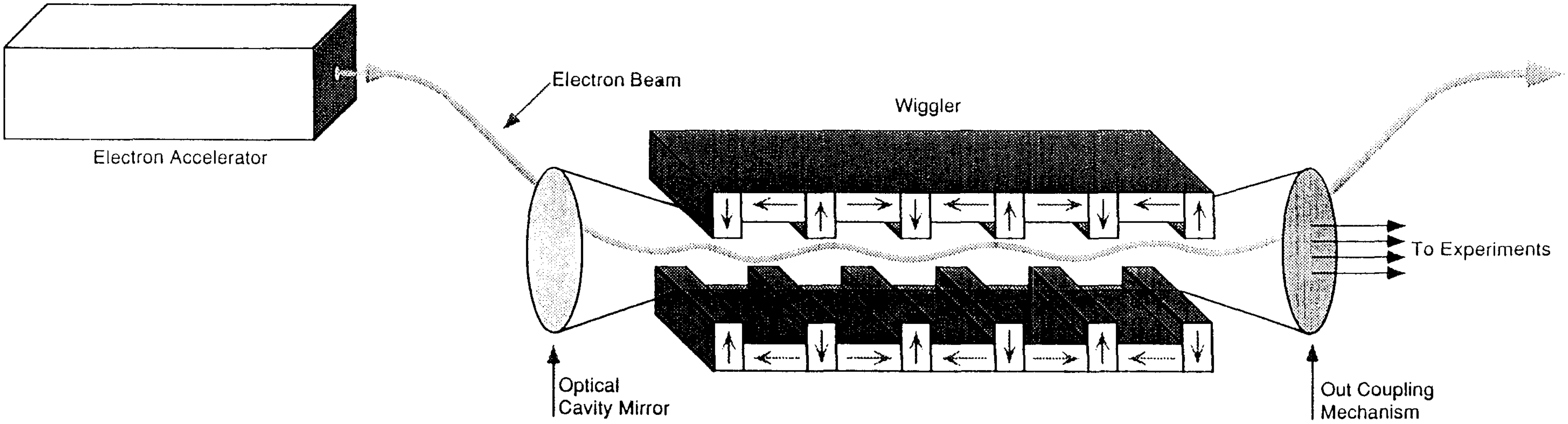

Electron Accelerator
Electron Beam
Wiggler
To Experiments
Optical
Cavity Mirror
Out Coupling
Mechanism

Fig. 1

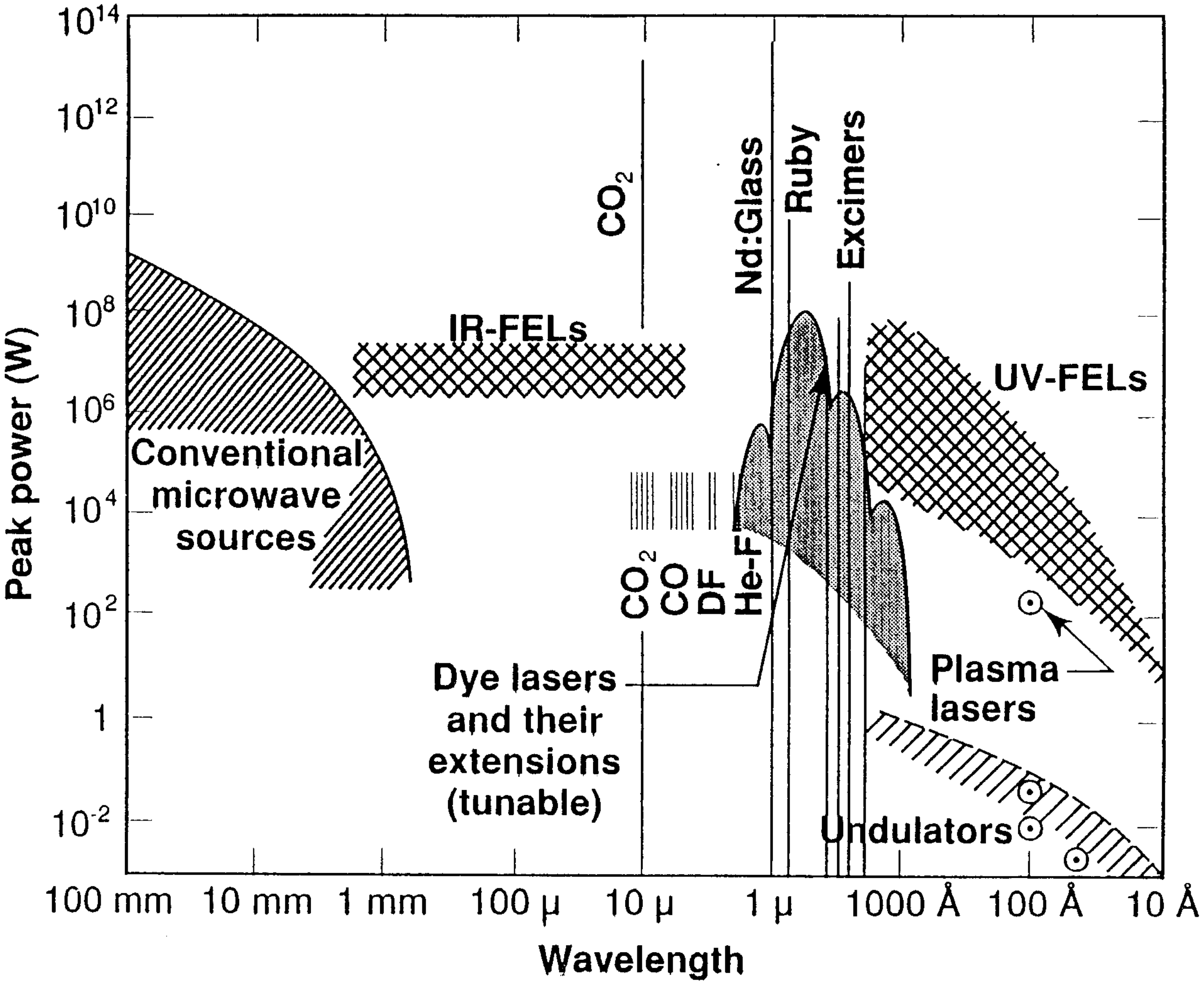
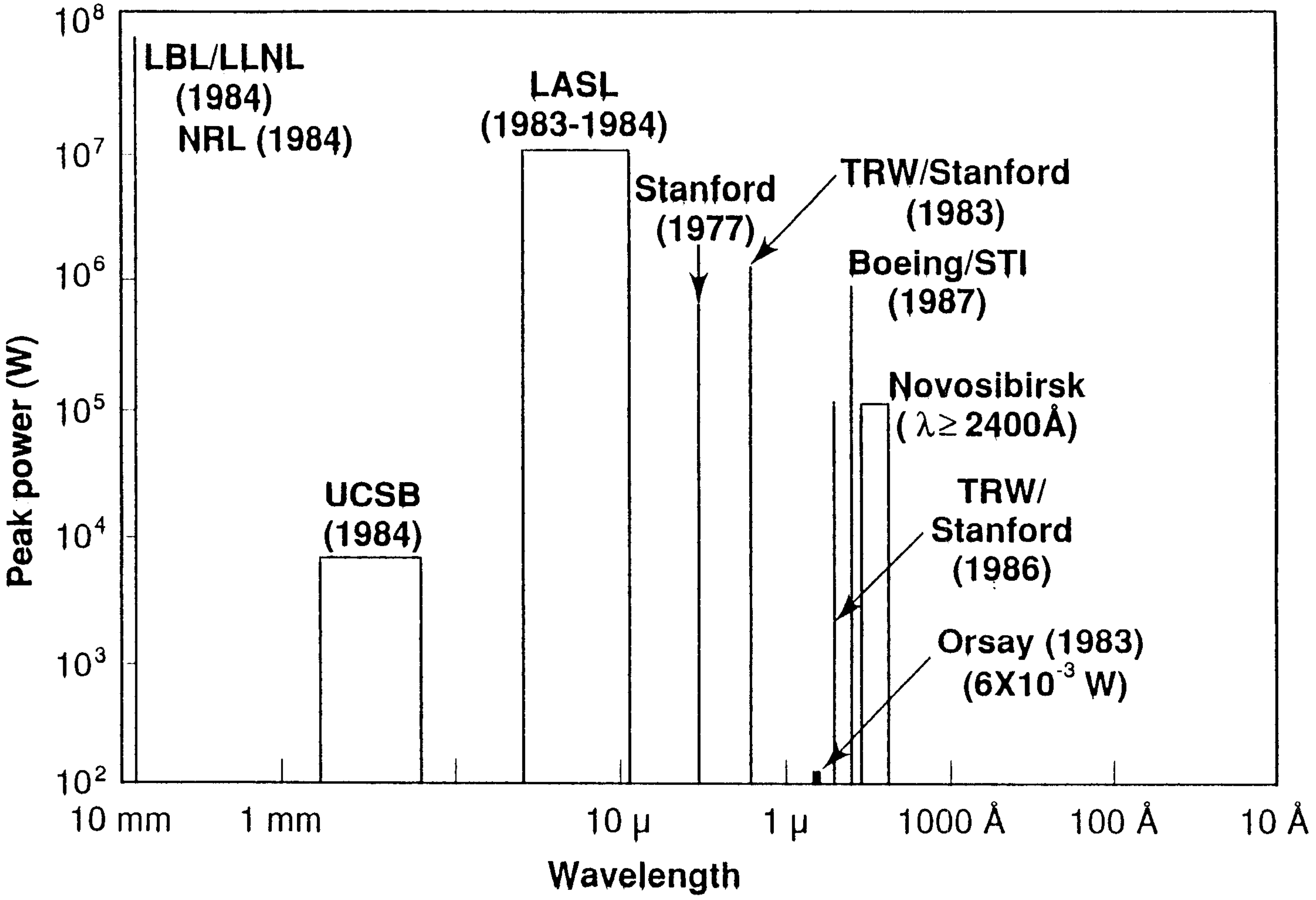

10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
Peak power (W)
100 mm
10 mm
1 mm
100 μ
10 μ
1 μ
1000 Å
100 Å
10 Å
Wavelength
Conventional microwave sources
IR-FELs
CO_2
Nd:Glass
Ruby
Excimers
UV-FELs
CO_2
CO
DF
He-F
Dye lasers and their extensions (tunable)
Plasma lasers
Undulators

Fig. 2



LBL/LLNL (1984)
NRL (1984)
LASL (1983-1984)
Stanford (1977)
TRW/Stanford (1983)
Boeing/STI (1987)
Novosibirsk (λ≥ 2400Å)
UCSB (1984)
TRW/ Stanford (1986)
Orsay (1983) (6X10^-3 W)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
Peak power (W)
10 mm
1 mm
10 μ
1 μ
1000 Å
100 Å
10 Å
Wavelength

Fig. 3

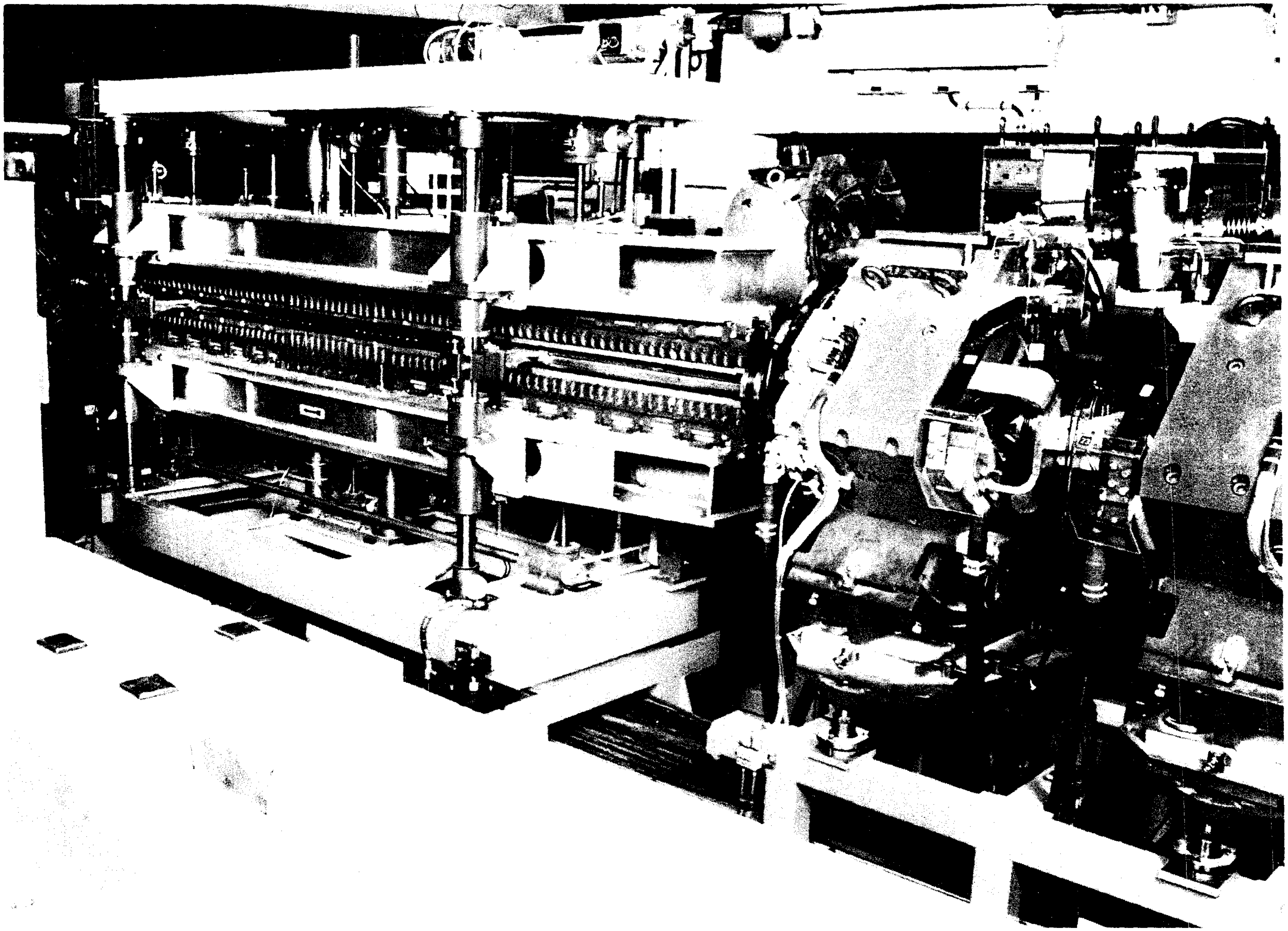


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Fig. 4