INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR/115 - 42*

WINTER COLLEGE ON LASERS, ATOMIC AND MOLECULAR PHYSICS

(21 January - 22 March 1985)

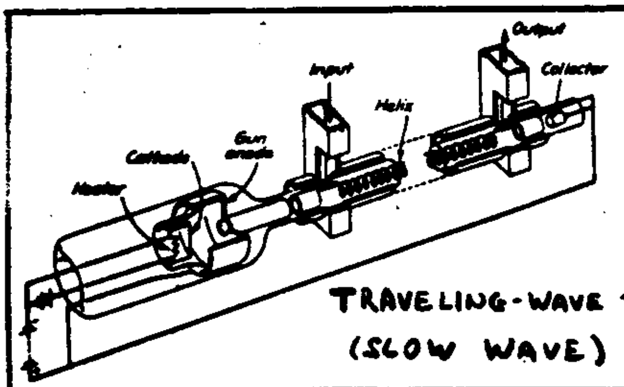
Topical Meeting on the Free Electron Laser

- SINGLE-PASS FEL DEVICES
- THE FREE ELECTRON LASER

E. SABIA
ENEA
Centro Ricerche Frascati
Casella Postale 65
00044 Frascati (Roma)
Italy

TOWARD SHORT WAVELENGTH COHERENT RADIATION

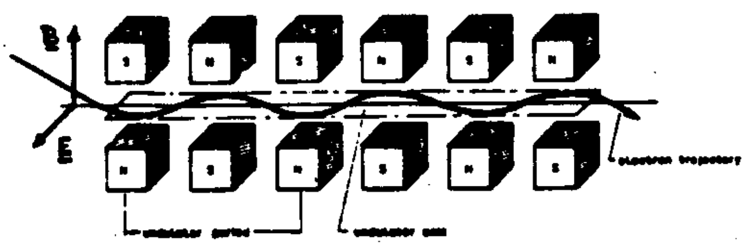
λ	SOURCE	OPERATING PRINCIPLE	LIMITS ON MINIMUM λ
$\gtrsim$ m	"TRIODE"	GRID DRIVEN E-BEAM MODULATION VIA A FEEDBACK CIRCUIT	CIRCUIT DIMENSION $\sim \lambda$ ELECTRON TRANSIT TIME $\sim 1/\omega$
$\gtrsim$ cm	KLYSTRON MAGNETRON TWT SLOW WAVE DEVICES	E-BEAM VELOCITY MODULATION VIA LONGITUDINAL ELECTRIC FIELD BUNCHING ⟶ COHERENT EMISSION	MINIATURIZATION OF RESONATING CAVITIES AND WAVEGUIDES
$\gtrsim$ mm	GYROTRON UBITRON FAST WAVE DEVICES	E-BEAM VELOCITY MODULATION VIA TRANSVERSE ELECTRIC FIELD BUNCHING ⟶ COHERENT EMISSION	E-BEAM QUALITY (ENERGY SPREAD, EMITTANCE)
FIR-IR VISIBLE UV	STANDARD LASER	STIMULATED EMISSION FROM BOUND STATES	LOW GAIN, MIRRORS, .
FIR-IR VISIBLE (UV & X)	FEL	FAST WAVE DEVICES OPERATING WITH RELATIVISTIC ELECTRONS DOPPLER SHIFT	GAIN $\propto \lambda^{3/2}$, MIRRORS, E-BEAM QUALITY.



$$\frac{d\mathcal{E}}{dt} = -e\,\underline{E}\cdot\underline{v} = -e\,E_L\cdot v_L \neq 0$$

TRAVELING-WAVE TUBE
(SLOW WAVE)

UBITRON & FEL (FAST WAVE)



$$\frac{d\mathcal{E}}{dt} = -e\,\underline{E}\cdot\underline{v} =$$

$$= -e\,E_T\cdot v_T \neq 0$$

$$(v_T \propto B)$$

$\underline{B}$ = UNDULATOR MAGNETIC FIELD $\propto \cos\left(\frac{2\pi}{\lambda_q} z\right)$

$\underline{E}$ = FAST WAVE ELECTRIC FIELD $\propto \cos(\omega t - kz)$

SLIDES 1,2,3

BRIEF PHYSICAL INSIGHT (HIGHLY RELATIVISTIC ELECTRONS + FREE WAVE)

ENERGY VARIATION $\frac{d\mathcal{E}}{dt} = -e\, v_T E_T$

v_T AND E_T ARE BOTH OSCILLATING (IN SPACE AND TIME) $\longrightarrow$

$$\begin{cases} v_T = \frac{e B_0 \lambda_q}{2\pi m c \gamma} \cos\left(\frac{2\pi}{\lambda_q} z\right) \\ E_T = E_0 \cos\left(\frac{2\pi c}{\lambda}(t - z/c)\right) \\ \left(\gamma = 1/\sqrt{1-(v/c)^2}\right) \end{cases}$$

IN GENERAL WE HAVE $\left\langle \frac{d\mathcal{E}}{dt} \right\rangle \sim 0$ UNLESS v_T & E_T OSCILLATE AT NEARLY THE SAME FREQUENCY. NAMELY v_T AND E_T READ ($v_0 = \langle v_z \rangle$) ($z = v_0(t - t_0)$)

$$v_T = \frac{e B_0 \lambda_q}{2\pi m c \gamma} \cos\left(\frac{2\pi v_0}{\lambda_q}(t - t_0)\right), \quad E_T = E_0 \cos\left(\frac{2\pi c}{\lambda}\left(\left(1 - \frac{v_0}{c}\right)t + \frac{v_0}{c} t_0\right)\right)$$

SYNCHRONISM CONDITION $\longrightarrow \frac{2\pi v_0}{\lambda_q} = \frac{2\pi c}{\lambda}(1 - v_0/c)$

$$\lambda = \lambda_q\left((v_0/c)^{-1} - 1\right) \longrightarrow (v_0 \sim c) \quad \lambda \ll \lambda_q$$

$$\frac{d\mathcal{E}}{dt} \sim -\frac{e^2 B_0 E_0 \lambda_q}{4\pi m c \gamma} \cos\left(\frac{2\pi c}{\lambda} t_0\right) \longrightarrow \text{ENERGY MODULATION}$$

DRIFT SPACE $\longrightarrow$ LONGITUDINAL BUNCHING $\longrightarrow$ COHERENT EMISSION

FEL SOURCES (SHORT WAVELENGTH)

- RAMAN (PLASMA WAVE EXCITATION)
- COMPTON (SINGLE PARTICLE)
- CERENKOV (MEDIA)
- OROTRON (SMITH–PURCELL EFFECT)

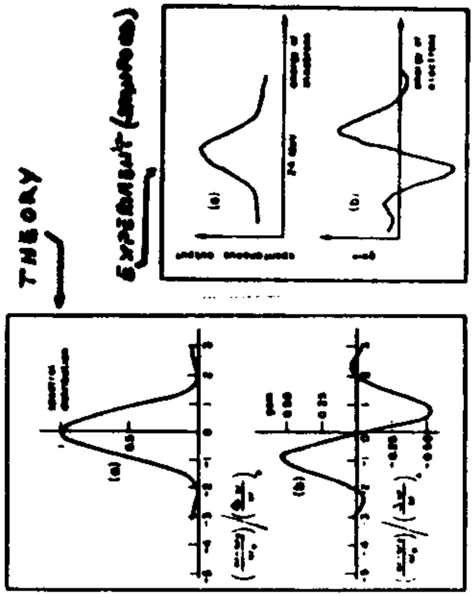
MAIN FEL PARAMETERS

		TYPICAL VALUES
UNDULATOR PARAMETER	$K = \frac{e B \lambda_q}{2\pi m c^2}$	0.1 — 1
OPERATING WAVELENGTH **TUNABILITY**	$\lambda = \frac{\lambda_q}{2\gamma^2}(1+K^2)$	0.5 — 10 μm
SPONTANEOUS EMISSION LINEWIDTH	$\left(\frac{\Delta\omega}{\omega}\right)_0 = \frac{1}{2N}$ $\left(N = \frac{L}{\lambda_q}\right)$	0.1 — 1 %

GAIN ∝ DERIVATIVE OF THE SPONTANEOUS EMISSION SPECTRUM (MADEY'S THEOREM)

$$\hat{g} \propto \frac{\lambda^{3/2}}{\lambda_q^{5/2}} L^3 n_e \frac{K^2}{(1+K^2)^{3/2}}$$

THEORY



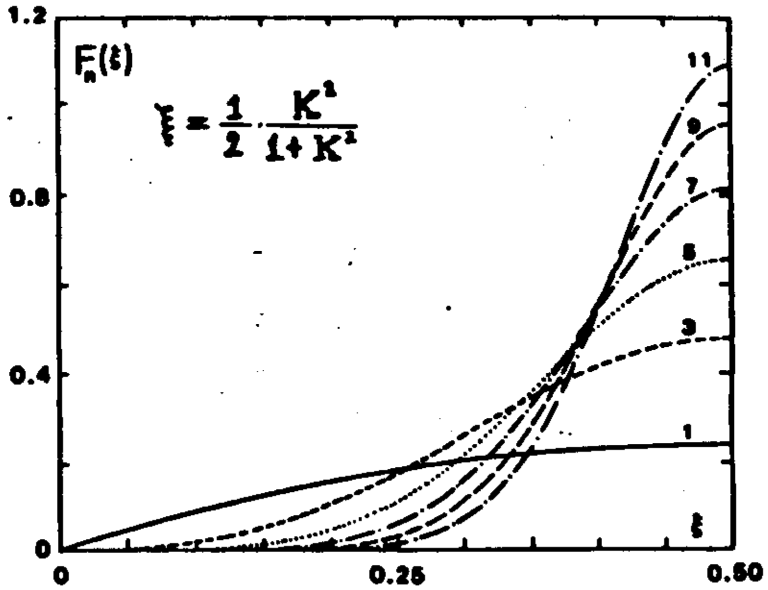
EXPERIMENT (SPONTANEOUS)

EFFICIENCY $\eta \sim \left(\frac{\Delta\gamma}{\gamma}\right) \sim \left(\frac{\Delta\lambda}{\lambda}\right)_{MAX} \simeq \frac{1}{2N} \left(\frac{\Delta\omega}{\omega}\right)_0$

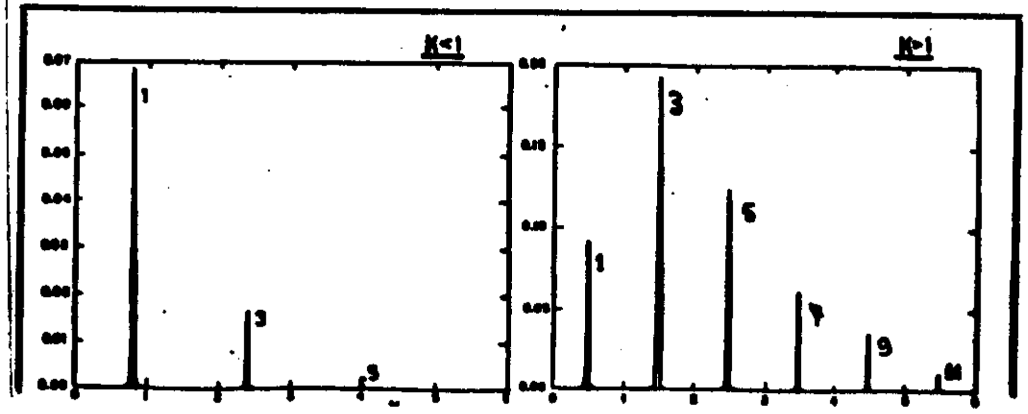
MAX ELECTRON ENERGY DISPLACEMENT IN THE GAIN CURVE (SYNCHRONISM CONDITION)

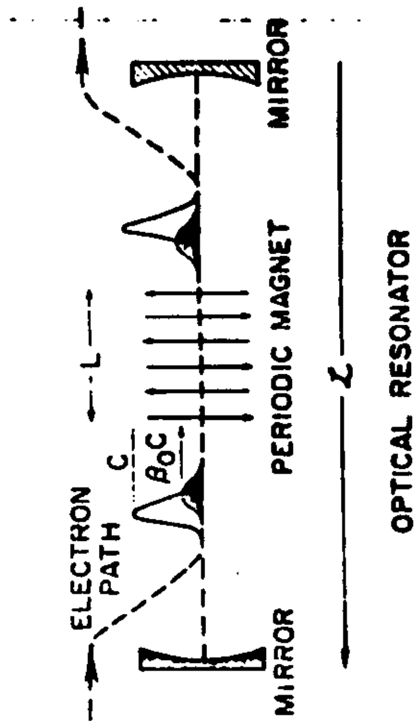
$$P[W] = \eta\, \mathcal{E}[eV] \cdot I[A]$$

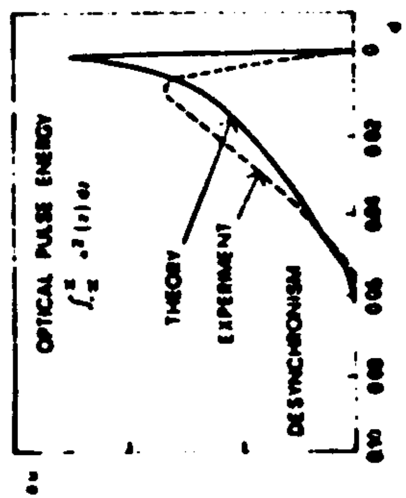
HIGHER HARMONICS OPERATION (LINEAR UNDULATOR)



$$\lambda = \frac{1}{n}\cdot\frac{\lambda_q}{2\gamma^2}(1+K^2), \quad n = 1, 3, 5, \ldots$$







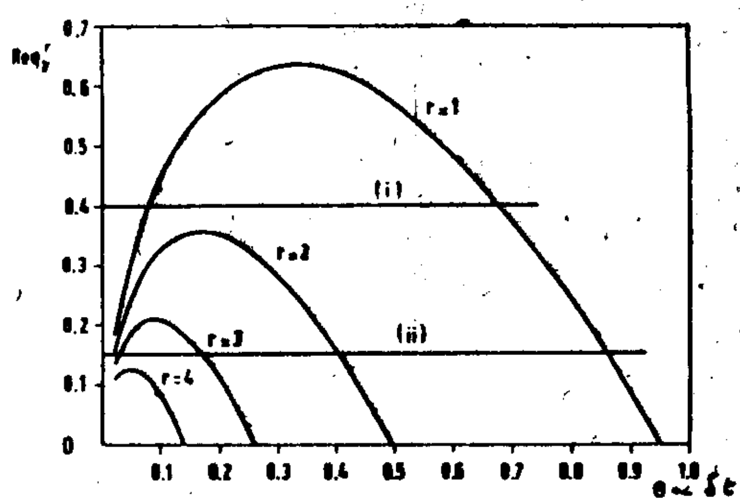


FIG. 8

$Re\, q_\gamma^r$ VS Θ FOR THE FIRST FOUR SMs (μ_c = 1.0)

CURVE (i) γ_T/g_Q = .4

CURVE (ii) γ_T/g_Q = .15

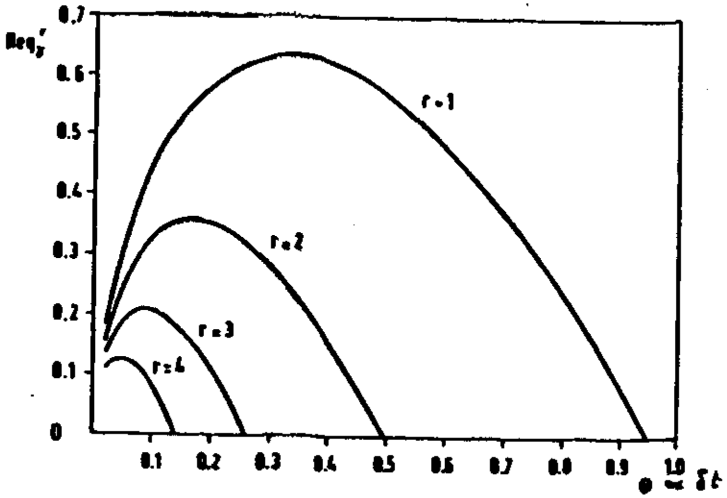


FIG. 5

Re q_γ^r VS θ FOR THE FIRST FOUR SMs

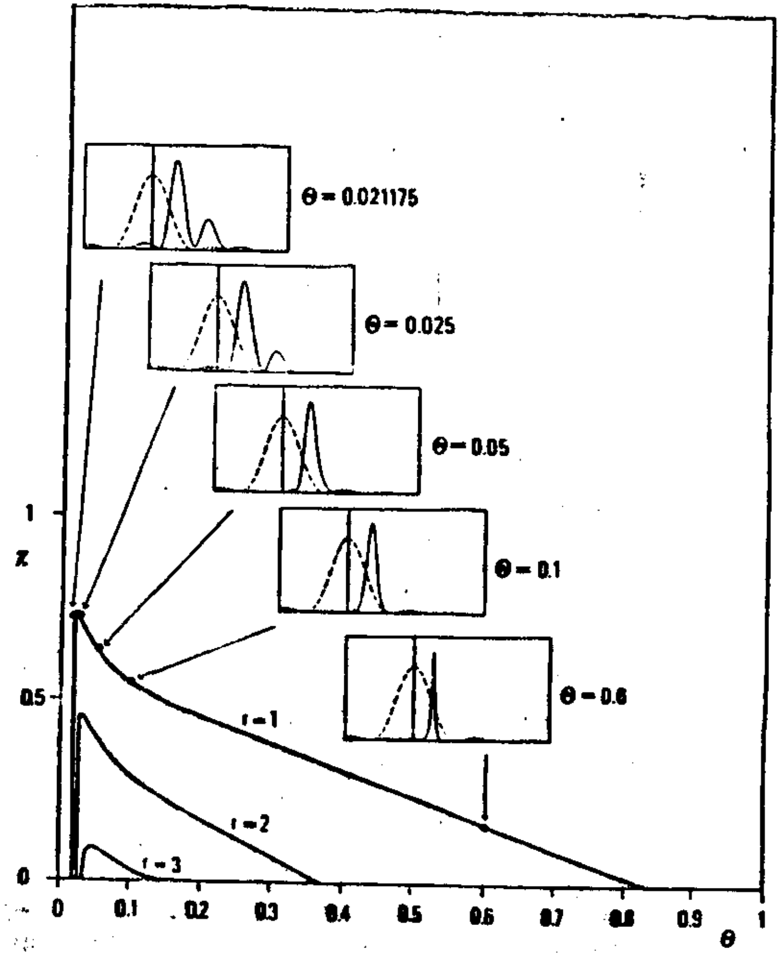


FIG. 11

χ VS θ AND LASER SPECTRUM FOR r = 1 (γ_T/θ_p = .15)

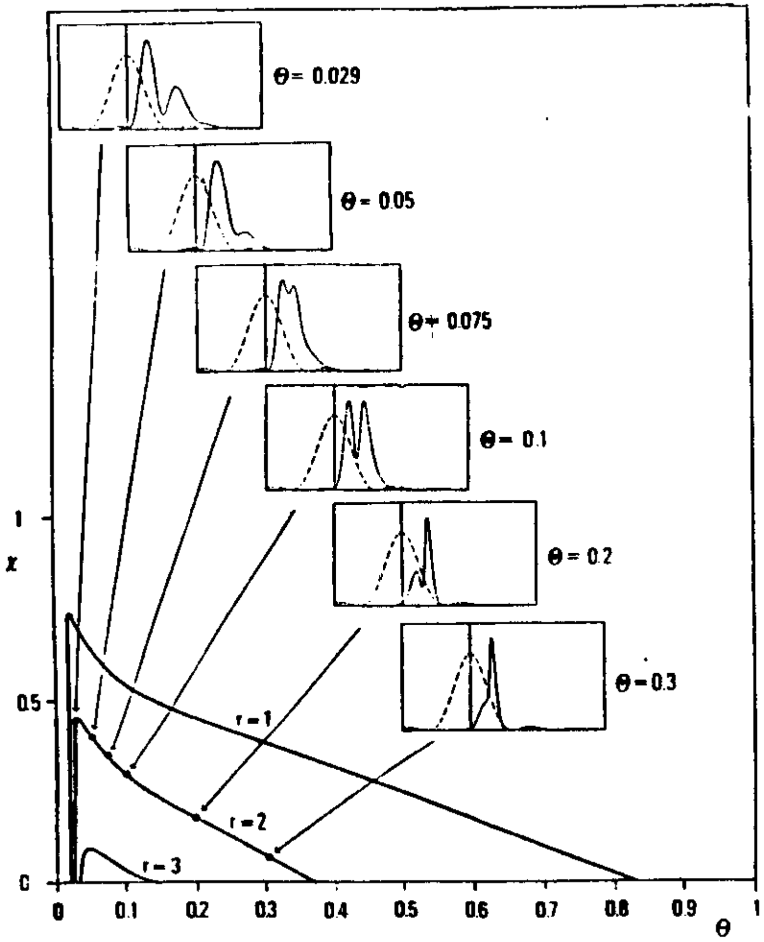


FIG. 12

χ VS Θ AND LASER SPECTRUM FOR r = 2 (γ_T/g_o = .15)

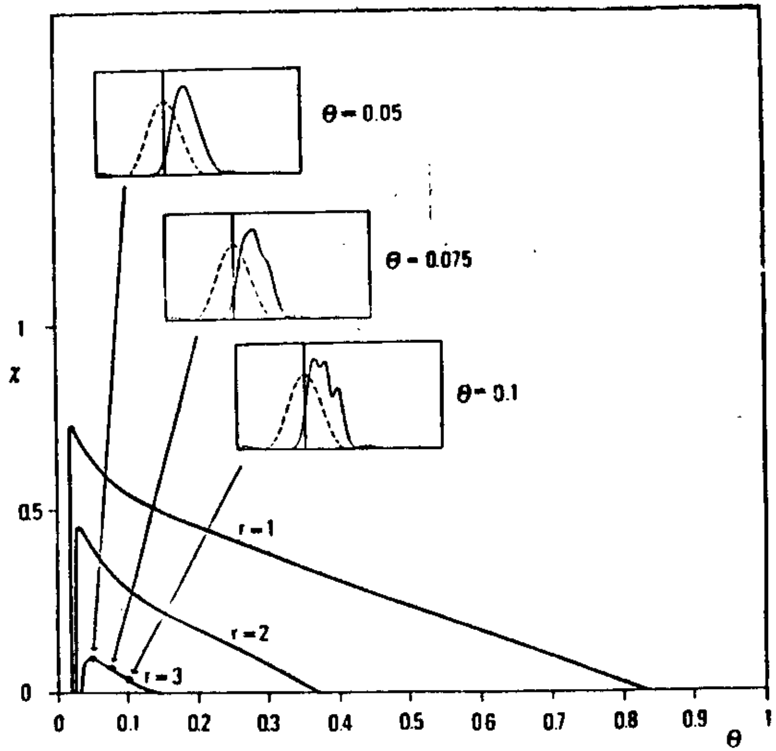


FIG. 13

χ VS Θ AND LASER SPECTRUM FOR r = 3 (γ_T/g_o = .15)

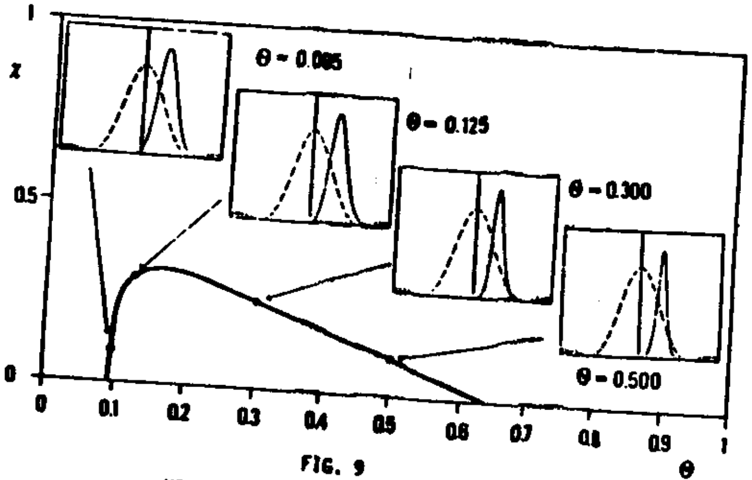
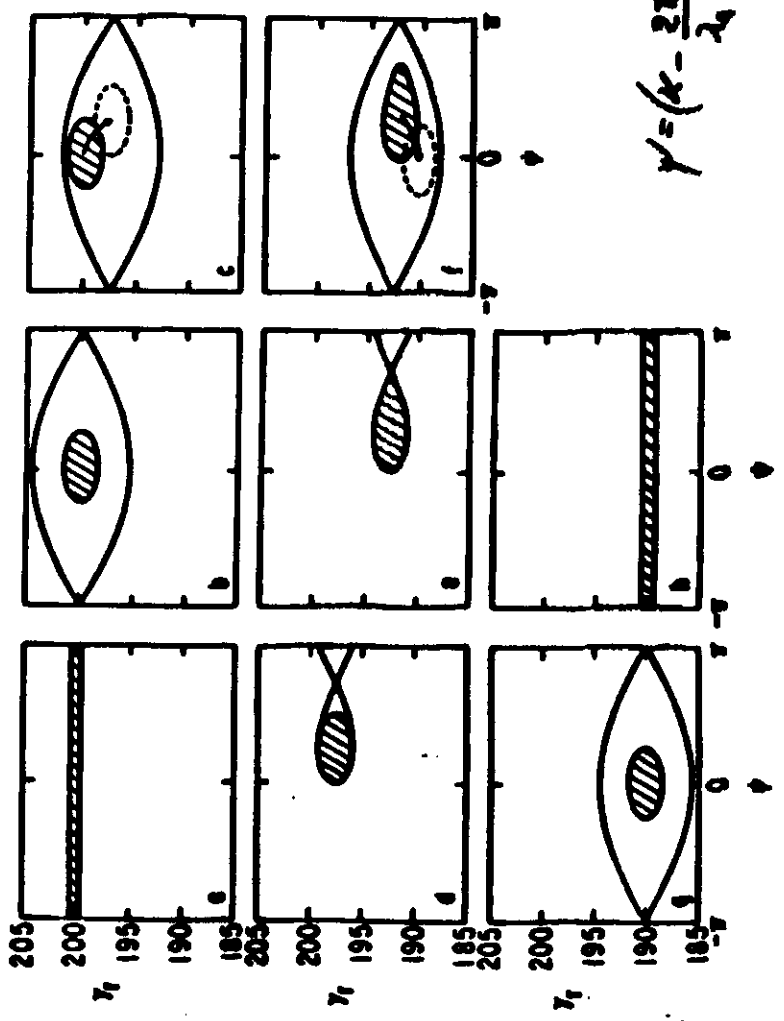


FIG. 9
X VS Θ AND LASER SPECTRUM ($\gamma_T/g_0 = .4$)

- G. Dattoli, A. Marino, A. Renieri, F. Romanelli, IEEE Quantum El. QE-17, 1371 (1981)



$$\psi = \left(k - \frac{2\pi}{\lambda_q}\right) z - \omega t - \phi$$

N.M. Kroll, P. Morton and M.N. Rosenbluth : IEEE J. Quantum Electr. QE-17 (1981)

STANFORD EXPERIMENT

1971 PROPOSAL

J.M.J. MADEY (J. Appl. Phys. 42, 1906)

1976 AMPLIFIER (λ=10.6 μm)

L.R. ELIAS
W.M. FAIRBANK
J.M.J. MADEY
H.A. SCHWETTMAN
T.I. SMITH

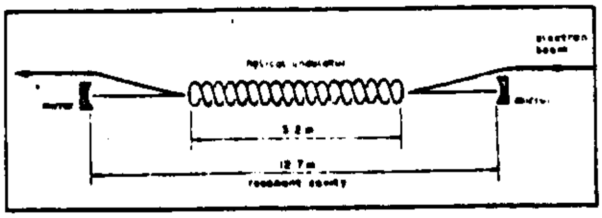
(Phys. Rev. Lett. 36, 717)

1977 OSCILLATOR (λ=3.3 μm)

D.A.G. DEACON
L.R. ELIAS
J.M.J. MADEY
G.J. RAMIAN
H.A. SCHWETTMAN
T.I. SMITH

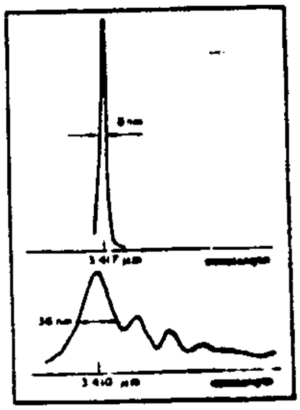
(Phys. Rev. Lett. 38, 892)

FEL LAYOUT



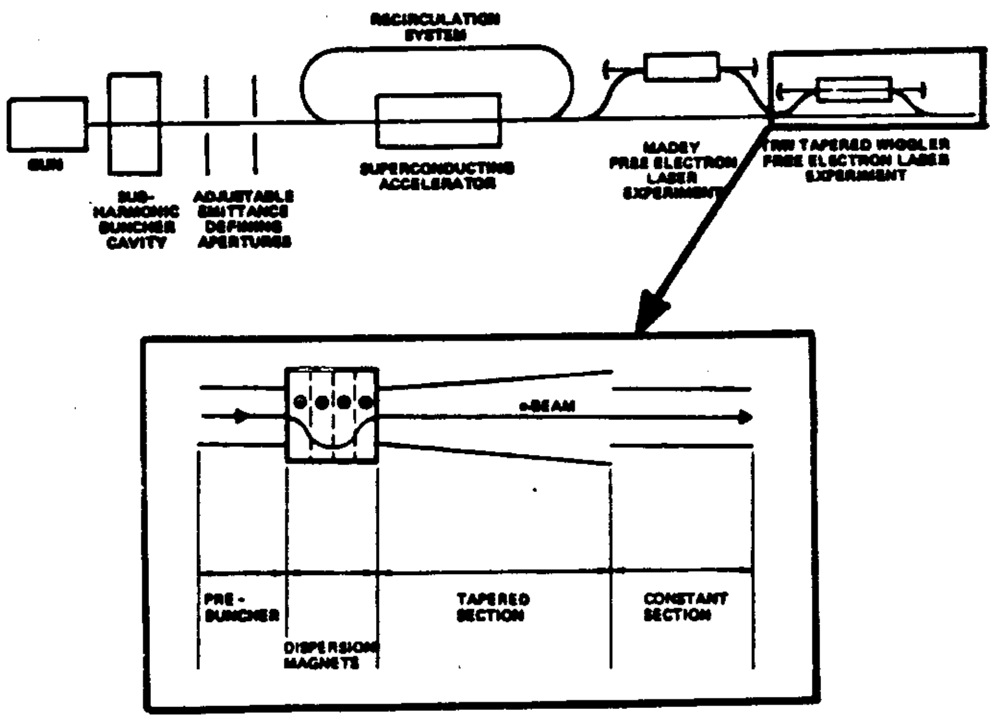
LASER SPECTRUM

SPONTANEOUS EMISSION SPECTRUM



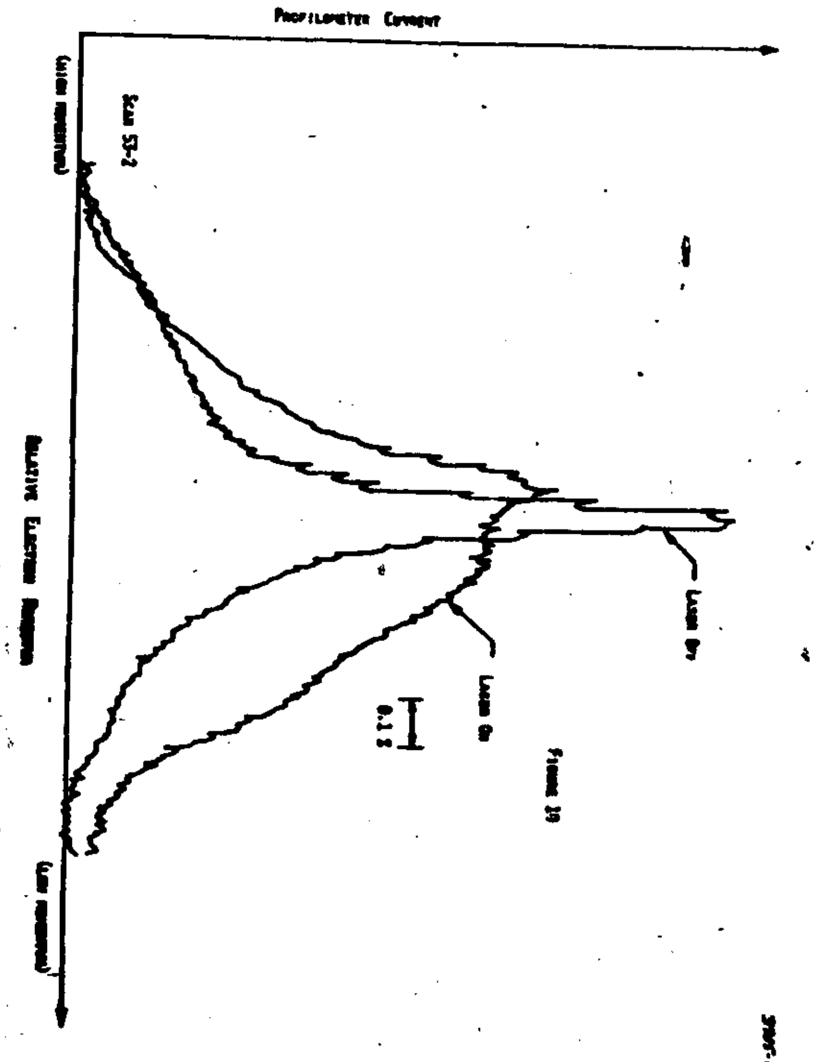
SLIDES 6,7,8,9

TRW



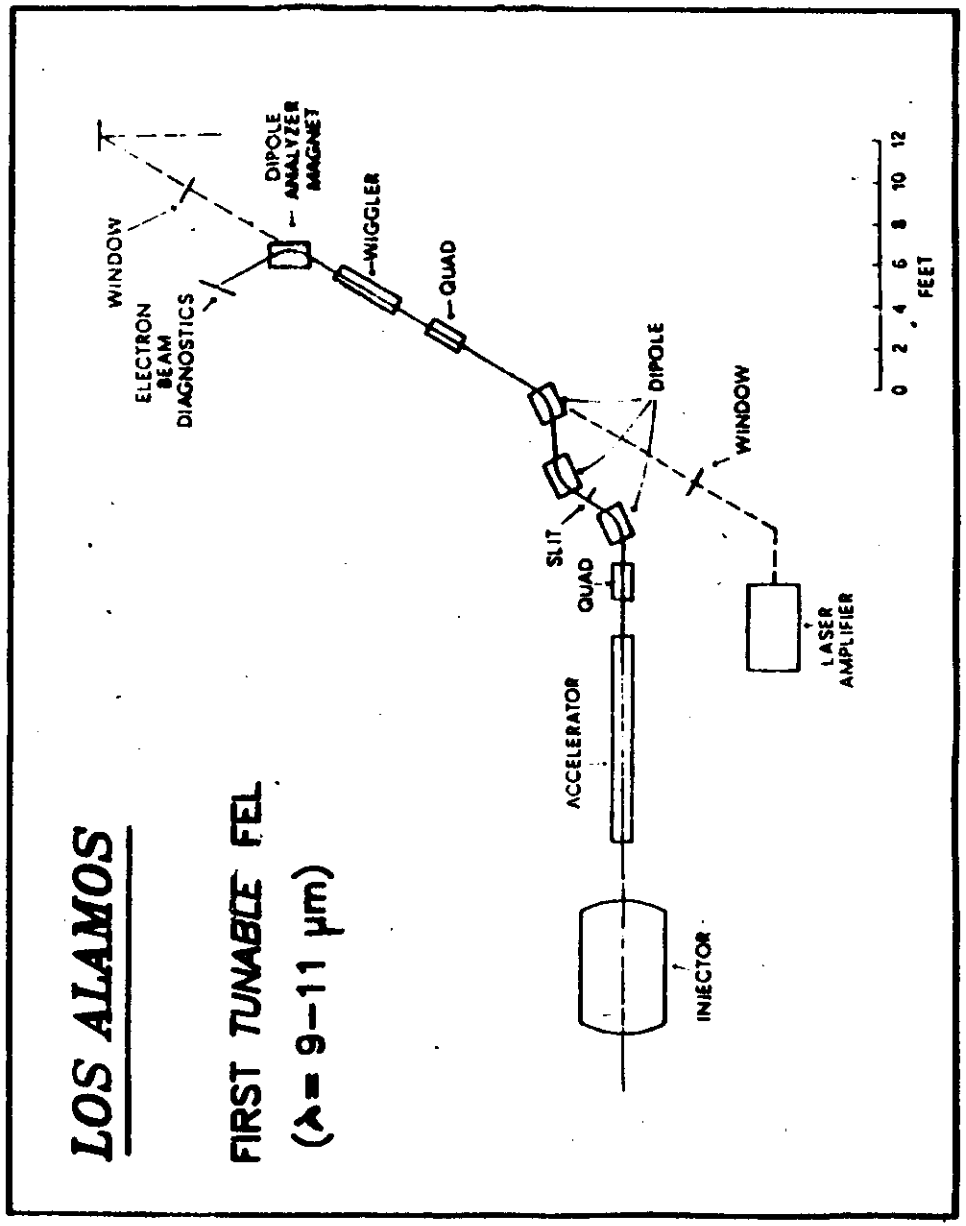
"MULTICOMPONENT" UNDULATOR

- 17 -



Profilometer Current
Laser On
Laser Off

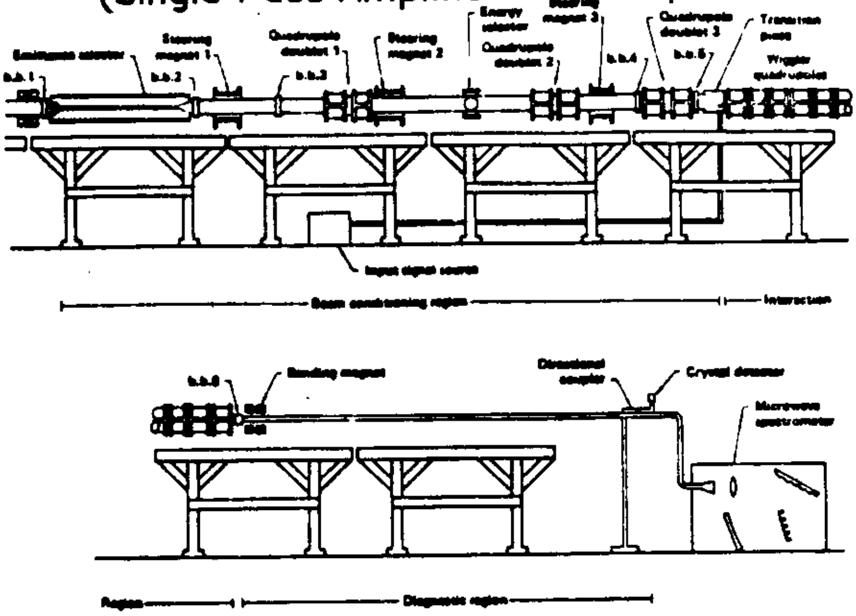
-18-



LOS ALAMOS
FIRST TUNABLE FEL
(λ= 9–11 μm)
WINDOW
ELECTRON BEAM DIAGNOSTICS
DIPOLE ANALYZER MAGNET
WIGGLER
QUAD
DIPOLE
WINDOW
SLIT
QUAD
LASER AMPLIFIER
ACCELERATOR
INJECTOR
0 2 4 6 8 10 12
FEET

LIVERMORE (ELF)

- VERY HIGH GAIN --> EXPONENTIAL REGIME
- NO OPTICAL CAVITY
  (Single Pass Amplification of Spontaneous Emission)



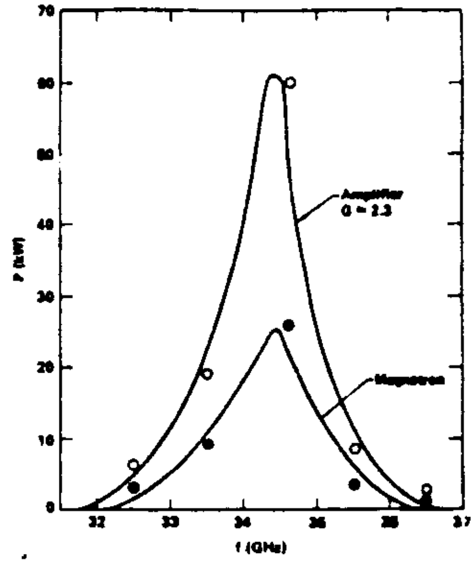
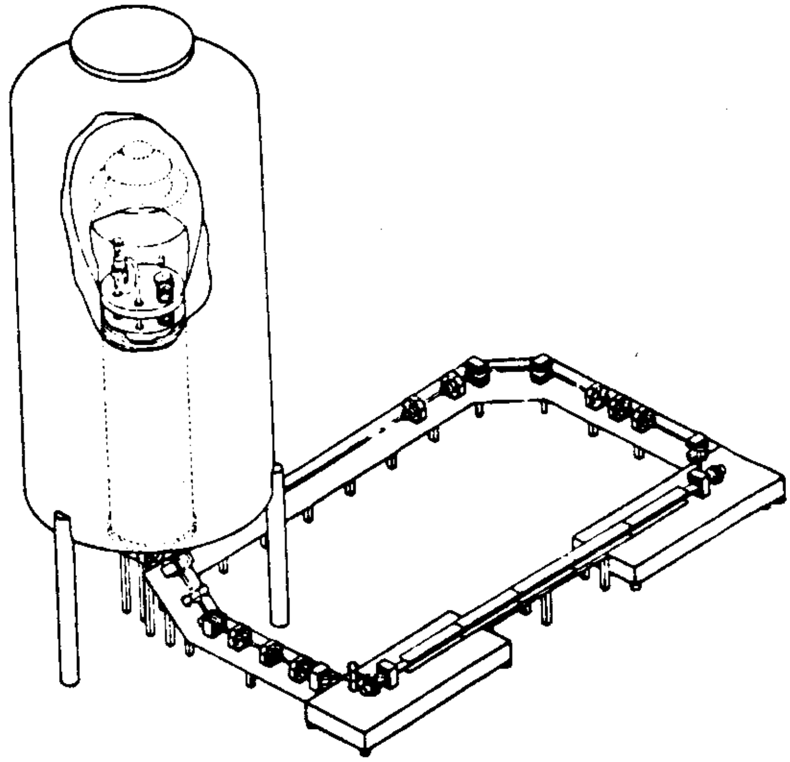


FIG. 1 Diagram of the Electron Laser Facility

S. BARBARA

- CW OPERATION WITH RECIRCULATED ELECTRON BEAM

- 2–STAGES OPERATION WITH A FEL WAVE IN PLACE OF AN UNDULATOR MAGNET



- FEL AS DRIVER FOR LASER ACCELERATION

STATUS OF ART

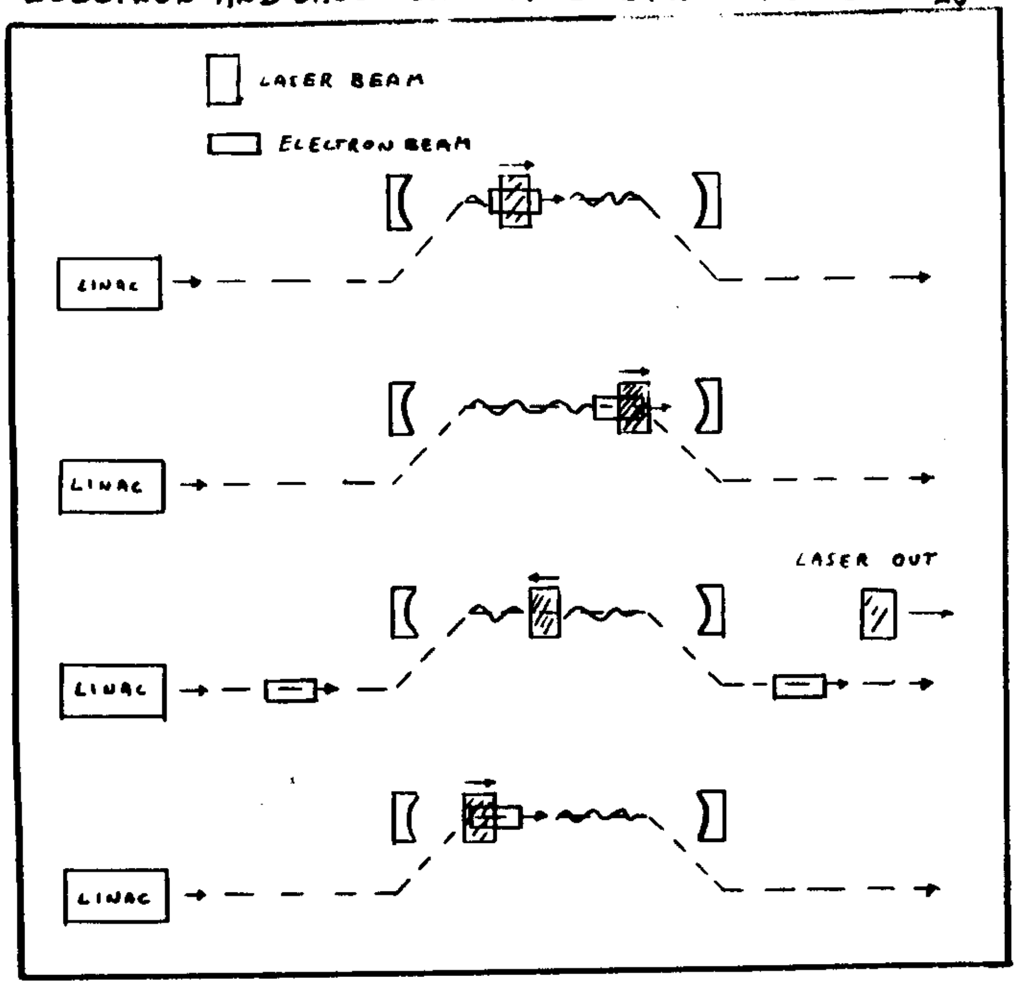
(1984 FEL CONFERENCE, CASTELGANDOLFO, ITALY)

YEAR	LABORATORY	ACCEL.	E(MeV)	λ(μm)	τ(psec)	T(μsec)	$\hat{P}$ (W)
1977	STANFORD	S.C. LINAC	43	3.3	4	$\sim 10^3$	$\sim 10^6$
1983	ORSAY	S.R. ACO	160	0.65	500-1000	C.W.	1
1983	TRW	S.C. LINAC	66	1.6	4	$\sim 10^3$	$\sim 10^6$
1983	LOS ALAMOS	LINAC	20	9-11	30	70	10^6
1983	LIVERMORE	INDUCT. LINAC	4.5	8×10^3	3×10^4	—	8×10^7
1984	S. BARBARA	PELLETRON	3	400	60×10^6	—	5×10^{-3}

FEL SCENARIO

	(μm)	ACCELERATOR	E (MeV)	I (A)	UNDULATOR	λ_q(cm)
LIVERMORE	$(2-10) \cdot 10^3$	Induction Linac	4	10	Pulsed (Tapered)	9.8
S.BARBARA 1–stage	100–360	Pelletron	3–6	2	Permanent Magnet	3.6
S.BARBARA 2–stages	1–10	Pelletron	3	2	FEL Laser Wave	0.01–0.1
BELL LABS	100–400	Microtron	18–20	5	Electromagnet	20
FRASCATI (ENEA)	10–30	Microtron	20	6.5	Permanent Magnet	5
UK PROJECT	2–20	Linac	20–100	10	Permanent Magnet	8
TRW	10.6	S.C. Linac	66	2.5	Permanent Magnet	3.56
LOS ALAMOS	9–11	Linac	20	25	Permanent Magnet	2.4
MSNW–BAC	10.6	Linac	19	100	Permanent Magnet	2.54–2.22
STANFORD	3.3	S.C. Linac	43	1.3	S.C. Electromagnet	3.23
NOVOSIBIRSK	0.6328	S.R. VEPP–III	370		Permanent Magnet	10
ORSAY	0.65	S.R. ACO	166		Permanent Magnet	7.78
FRASCATI (INFN)	0.5145	S.R. ADONE	300,624		Electromagnet	11.6
BROOKHAVEN	0.25–0.45	S.R. VUV Ring	300–500		Permanent Magnet	6.5

ELECTRON AND LASER BEAM TIME STRUCTURE



LASER BEAM SPECTRUM

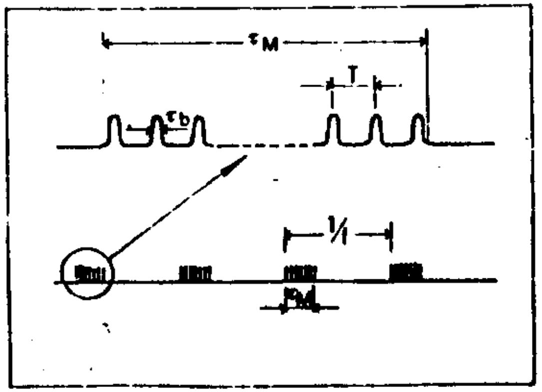
$$\frac{\Delta\lambda}{\lambda} \sim \frac{\lambda}{c\tau_b}$$

(FOURIER TRANSFORM LIMITED)

$\tau_b \sim 20$ psec , $T = 300$ psec

$\tau_M \sim 12$ μsec

$f_{MAX} \sim 150$ Hz



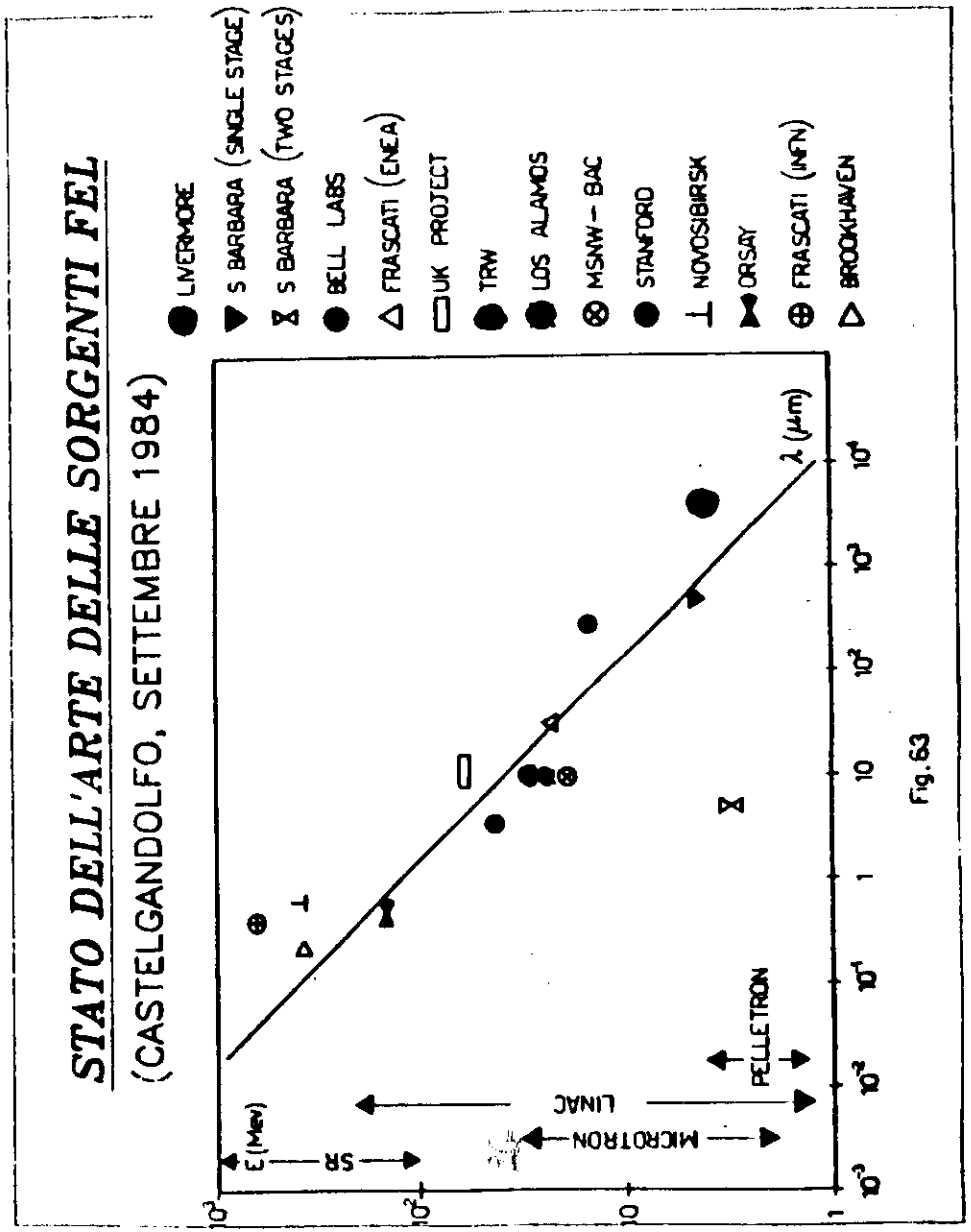


Fig. 63

THE FREE ELECTRON LASER EXPERIMENT AT THE ENEA FRASCATI CENTER

U. BIZZARRI, F. CIOCCI, G. DATTOLI, A. DE ANGELIS
E. FIORENTINO, G.P. GALLERANO, T. LETARDI
A. MARINO, G. MESSINA, A. RENIERI, E. SABIA
A. VIGNATI

ENEA

TIB – DIV. FISICA APPLICATA – FRASCATI
ITALY

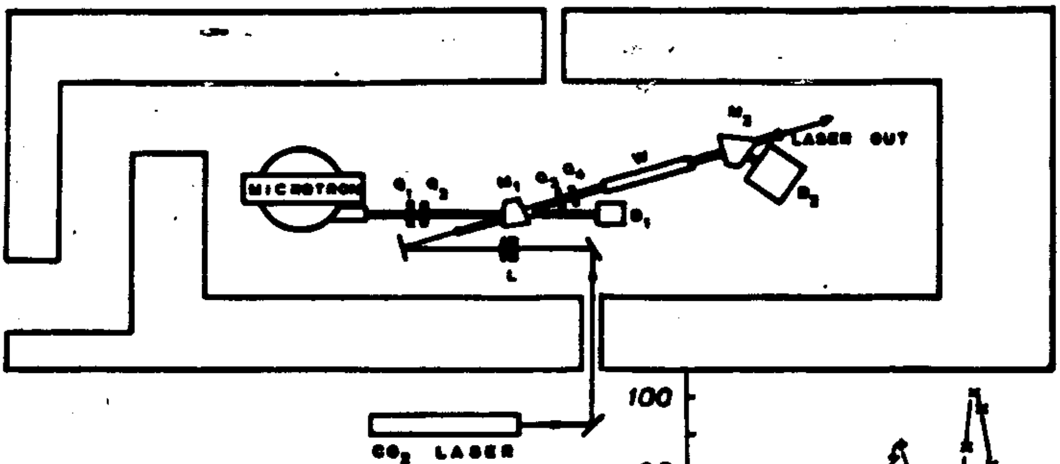
FRASCATI–ENEA

MAIN GOALS	E–BEAM	UNDULATOR
CO_2 LASER AMPLIFIER EXPERIMENT OSCILLATOR AT λ =10.6 μm PEAK GAIN = 4–12 % AVERAGE POWER = 0.1 W	E= 20 MeV I = 2–6.5 A FREQ. = 0.2 Hz	HELICAL PULSED PERIOD = 2.4 cm FIELD = 2.2 kG
TUNABLE OSCILLATOR (λ = 10–30 μm) PEAK GAIN = 10–30 % AVERAGE POWER = 1–100 W	E = 15–20 MeV I = 6.5 A FREQ.=1.5÷150 Hz	PERMANENT MAG. PERIOD = 5 cm FIELD = 3–6 kG

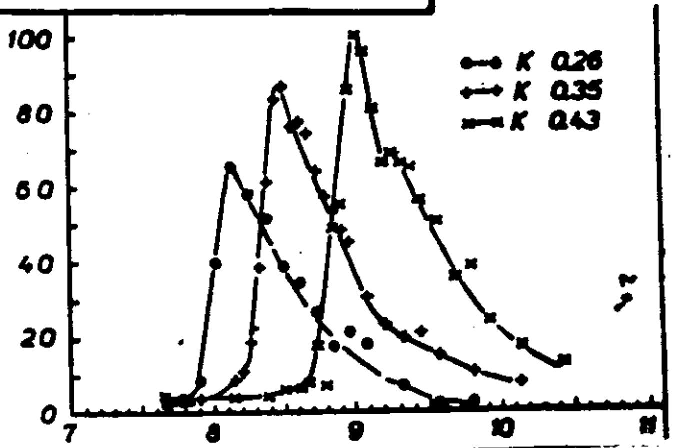
TUNABILITY ACHIEVED BY
- HIGH ORDER HARMONICS EMISSION
- VARIABLE UNDULATOR GAP (1.3–2.4 cm ––> K = 2–1)
- ELECTRON BEAM ENERGY TUNABILITY

FRASCATI–ENEA

– PULSED HELICAL UNDULATOR FEL EXPERIMENT



INTENSITY(a.u.)
VS
WAVELENGTH(μm)



MICROTRON PERFORMANCES

MAXIMUM ENERGY = 20 MeV
AVERAGE CURRENT (MAXIMUM) = 100 mA
MACROPULSE DURATION = 5 μsec
REPETITION FREQUENCY (MAXIMUM) = 10 Hz
ENERGY SPREAD = 0.12 %
HORIZONTAL EMITTANCE = 4π mm.mrad
VERTICAL EMITTANCE = 2π mm.mrad

MAIN PROBLEM

Oxidation and evaporation of LaB6 cathode inside the r.f. cavity requires cleaning of the cavity itself (in order to avoid discharges) every 50 hours for I < 50 mA and some hours at the maximum current

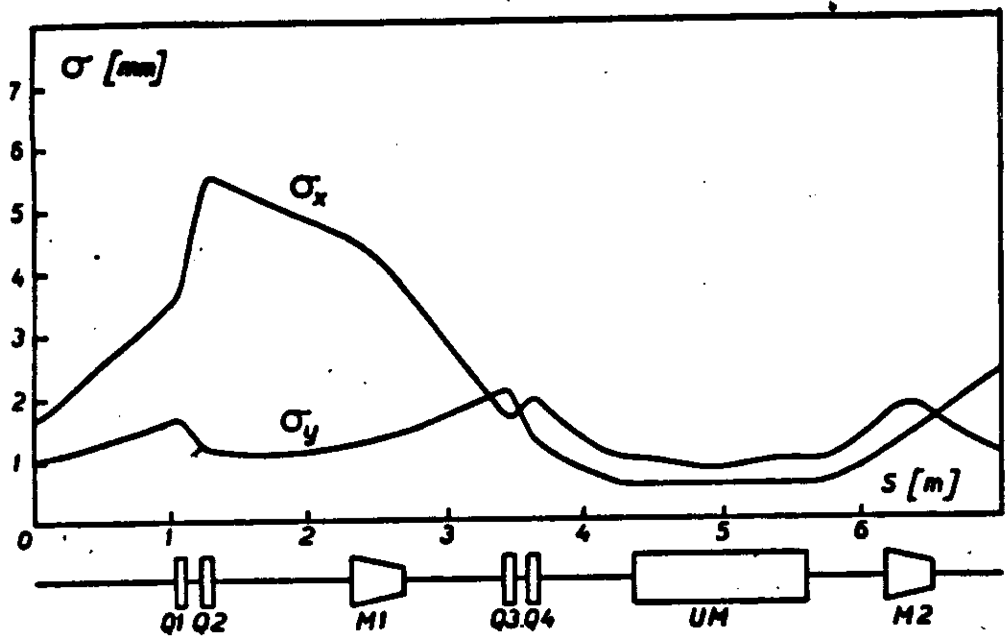
POSSIBLE SOLUTIONS UNDER INVESTIGATION

– Improuving of the vacuum ($5 \cdot 10^{-7}$ ---> 10^{-8})
– New cathodes (LaB6 Monocrystal, Borum)

E-BEAM TRANSVERSE DIMENSION

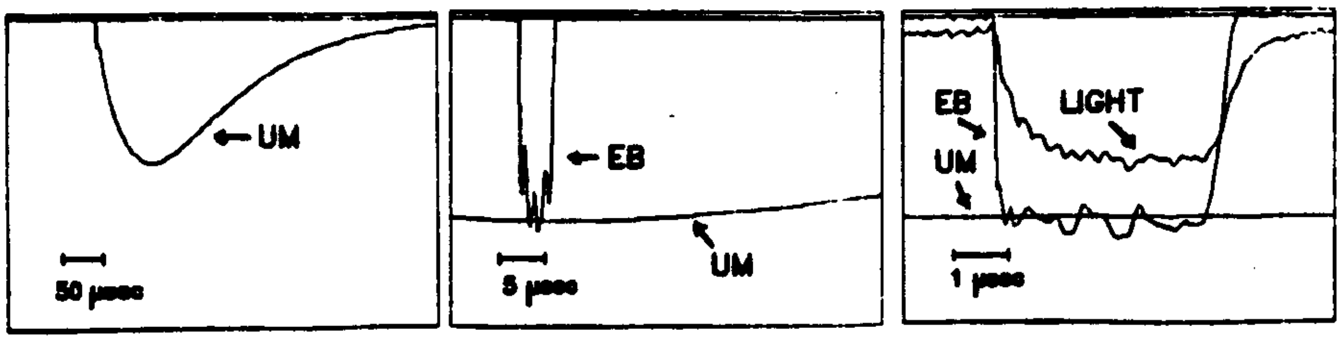
HORIZONTAL EMITTANCE = 4π mm.mrad
VERTICAL EMITTANCE = 2π mm.mrad
ENERGY SPREAD = 1.2 %
UNDULATOR PARAMETER K = 0.5

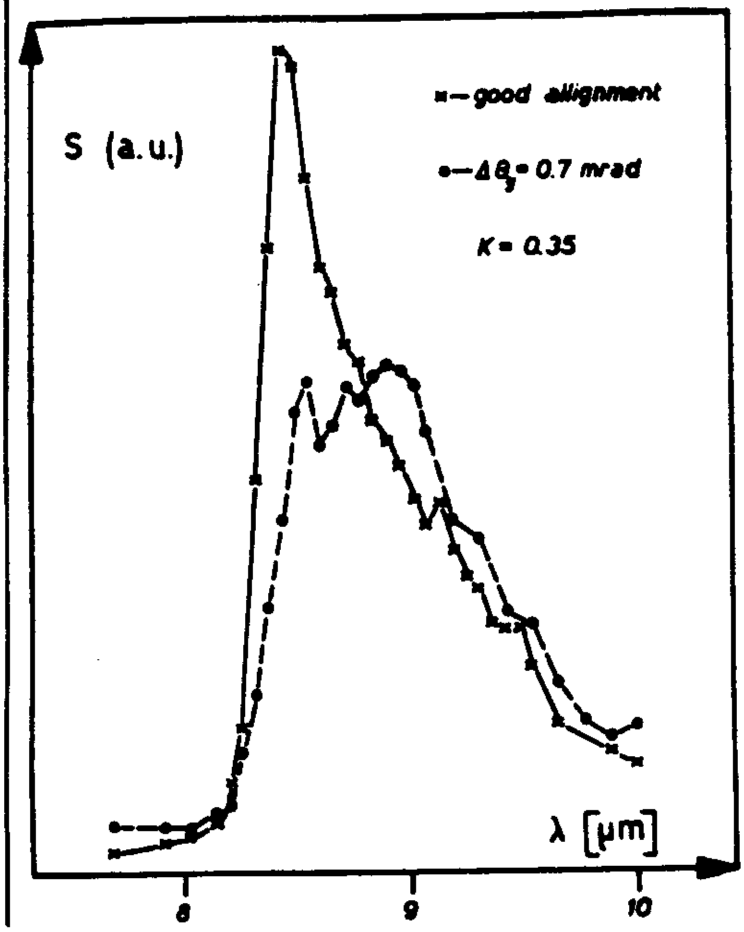
(STANDARD DEVIATION)



HELICAL UNDULATOR PARAMETERS

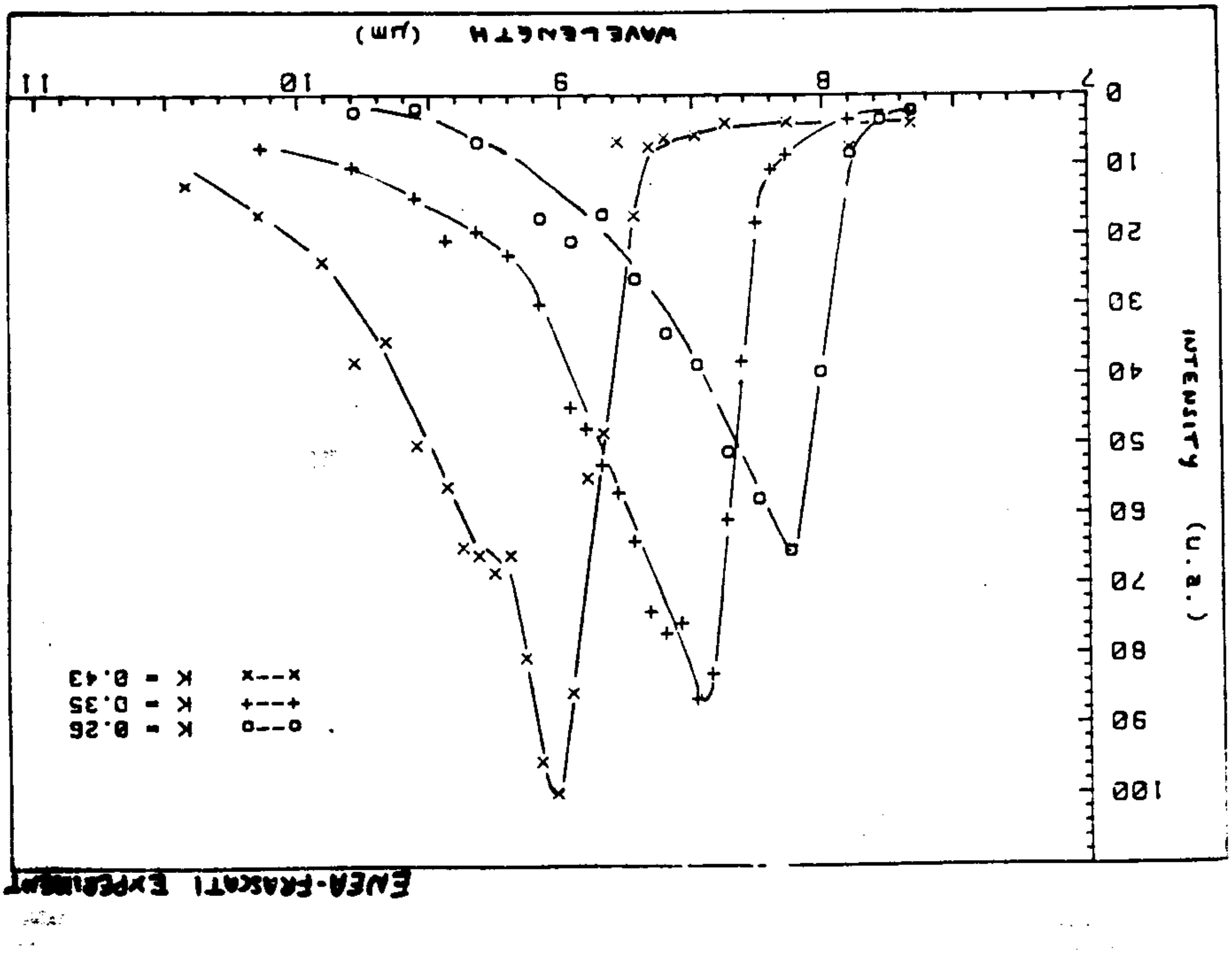
UNDULATOR PERIOD = 2.4 cm
UNDULATOR LENGTH = 1.2 m
MAGNETIC FIELD = 2.2 kG
UNDULATOR PARAMETER K = 0.5
HOMOGENEOUS WIDTH = 1 %
REPETITION FREQUENCY = 0.2 Hz

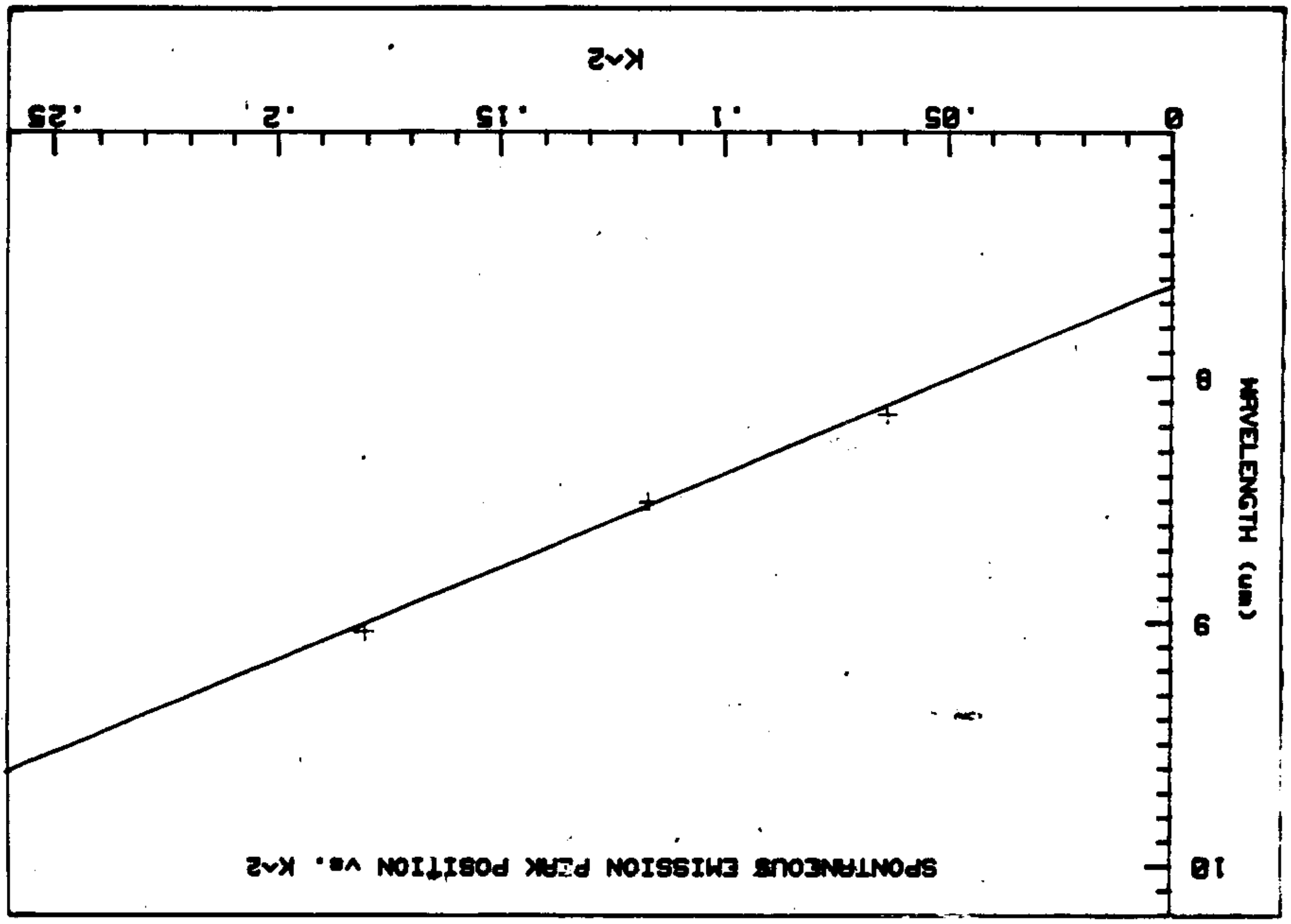




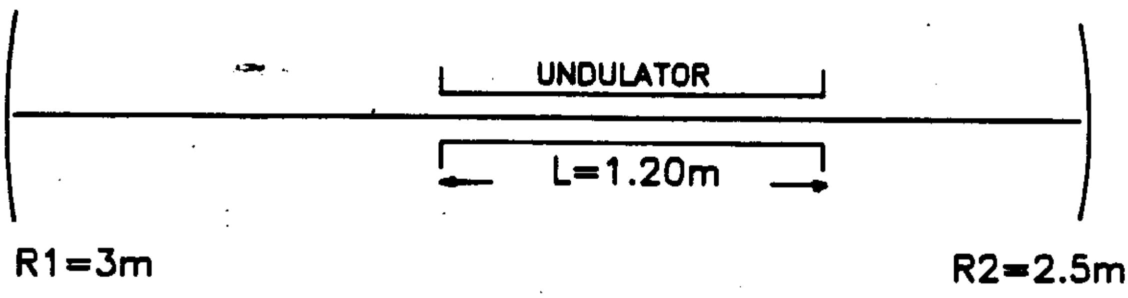
THE SPONTANEOUS EMISSION LINESHAPE STRONGLY DEPENDS ON THE E–BEAM ALLIGNMENT

IN THIS CASE THE LINEWIDTH INCREASES BY A FACTOR TWO WITH A MISALLIGNMENT OF 0.7 mrad





FEL OPTICAL CAVITY



MAIN CHARACTERISTICS:

1 – MIRROR SPACING $d = 5.10$ m

2 – STABILITY PARAMETER $g=(1-d/R1)(1-d/R2) = 0.7$

3 – UNDULATOR APERTURE $a = 2$ cm

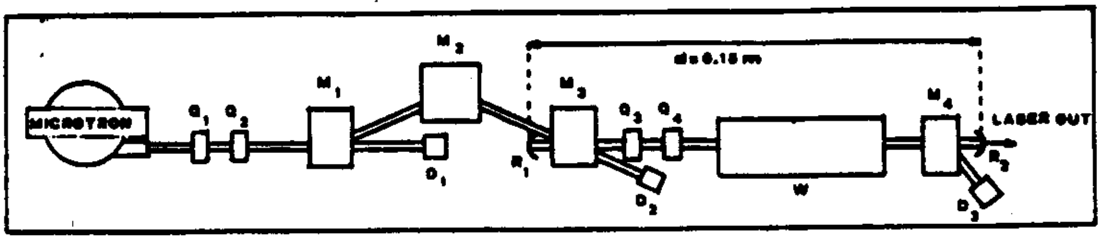
4 – UNDULATOR F–NUMBER $N=a^2/4\lambda L = 10$ AT $\lambda=10\mu m$

5 – R1 OUTPUT COUPLING (ZnSe + dielectric coating), r=98%

6 – R2 TOTAL REFLECTOR (copper), r=99%

FRASCATI–ENEA

– PERMANENT MAGNET UNDULATOR FEL EXPERIMENT



Q = QUADRUPOLES
M = BENDING MAGNETS
D = BEAM DUMPS
W = UNDULATOR
R = OPTICAL CAVITY MIRRORS

E.B. ACCELERATORS FOR S.P. DEVICES

E > 2 MeV

(1) ELECTROSTATIC ACCELERATORS
Energy limited (max energy 30 MeV)
Long pulses (up to seconds)
High quality E.B.
(energy spread and emittances)

(2) INDUCTION MACHINES
Max energy 50 MeV
(Technically higher energies may be reached)
Pulse duration limited 200 nsec
Very high current KA

(3) R.F. ACCELERATING MACHINES

(not superconducting)

Temporal microstructure in the E.B. at the R.F. accelerating frequency

(a) MICROTRONS

Long pulses
High peak current
High energy (Race—Track version)
Emittance Lawson—Penner limited
low energy spread (magnet selection)

(b) LINACS

Long pulse (klystron technology)
High peak current
Emittance Lawson—Penner limited

ELECTRON SOURCE	+	—
RF ACCELERATORS		
– SUPERCONDUCTING LINAC (STANFORD, TRW)	energy spread emittance	liquid helium
– LINAC (LOS ALAMOS, MSNW—BAC, UK)	emittance	energy spread
– MICROTRON (BELL LABS, FRASCATI—ENEA)	energy spread	emittance
– STORAGE RING (ORSAY, FRASCATI—INFN, BROOKHAVEN, NOVOSIBIRSK)	energy spread emittance high current	short straigth section recirculated e—beam high energy
CW ACCELERATORS		
– INDUCTION LINAC (LIVERMORE)	energy spread emittance very high current	low energy
– PELLETRON (S. BARBARA)	energy spread emittance	low energy recirculated e—beam

UNDULATOR MAGNET	+	−
ELECTROMAGNET		
– SUPERCONDUCTING (STANFORD, ORSAY)	small period, cw	liquid helium
– NORMAL CONDUCTING + IRON (FRASCATI–INFN, BELL LABS)	good field quality	large period power cons.
– PULSED (FRASCATI–ENEA, LIVERMORE)	small period, cheap	low rep. freq.
PERMANENT MAGNET		
– PURE REC MATERIAL (ORSAY, UK, LOS ALAMOS, TRW, NOVOSIBIRSK, S. BARBARA, FRASCATI–ENEA, BROOKHAVEN)	small period, cw no power cons. easy design ($\mu \sim 1$)	poor field homogeneity
– HYBRID (REC + IRON) (ORSAY, BROOKHAVEN), NOVOSIBIRSK	small period, cw no power cons. field homogeneity	design ($\mu >> 1$)
ELECTROMAGNETIC WAVE		
– FEL WAVE (S. BARBARA 2–STAGES)	field homogeneity very small period	low "k"

EXPERIMENTAL ASPECTS

– ELECTRON SOURCE
- HIGH CURRENT ($\sim$A)
- LOW ENERGY SPREAD ($\sim$ 0.1%)
- LOW EMITTANCE ($\sim$ 10mm*mrad)
- LONG MACROPULSE ($\sim$ 10μs)

– UNDULATOR MAGNET
- HIGH FIELD ($\sim$ kG)
- SMALL PERIOD ($\sim$ cm)
- GOOD FIELD HOMOGENEITY ($\sim 10^{-2}$)

– OPTICAL CAVITY
- VERY LARGE MIRROR SPACING ($\sim$ 10m)
- LOW LOSSES ($< 5\%$)

* VACUUM OPERATION RADIATION SHIELDING REMOTE CONTROL

CONCLUSION AND OUTLOOKS

MAIN FEATURES

- TUNABILITY
- EFFICIENCY (2% ---> 10-20%)
- HIGH PEAK POWER (1 MW ---> 1 TW)
- HIGH AVERAGE POWER (1 W ---> 1 kW)

BEST CANDIDATES (FOR IR)

- ELECTRON BEAM SOURCE ---> LINAC, MICROTRON
- UNDULATOR ---> HYBRID (PERMANENT MAGNET + IRON)

The free-electron laser

Alberto Renieri

The generation of coherent synchrotron radiation using beams of relativistic electrons passed through magnetic undulators opens up tremendous scope for photochemistry in general and isotopic separation by laser in particular. Applications for plasma heating in Tokamak-type installations to trigger off the controlled nuclear fusion process are also conceivable.

Early in 1977 John Madey and his team at Stanford University in California succeeded in generating coherent infrared light with a wavelength (λ) of 3.417 µm, a line width ($\Delta\lambda$) of 8 nm, and an average output (P) of 0.36 W. This new laser could now join the vast family of coherent radiation sources which ever since a beam of red light with a wavelength of 694.3 nm was produced by the first ruby laser in 1960 had been gradually growing by the addition of new devices operating within the band ranging from the far infrared to the ultraviolet. Viewed in this perspective, the parameters of the laser developed at Stanford were nothing exceptional. Nevertheless, the new source immediately aroused very considerable interest, because the active medium instead of being made up of atoms or molecules was nothing other than a beam of high-energy free electrons.

The emission of electromagnetic radiation by free charges

A laser based on light emission by free charges might be considered in principle as a contradiction of the laws of physics. We know that a free charge in a vacuum can neither emit nor absorb radiation, because the laws of energy and momentum conservation cannot be satisfied at one and the same time. However, this charge (and in what follows we virtually always understand charge as electron) is moving in an external field, the field itself absorbing some of the momentum and consequently rendering emission possible. Such a field could be the magnetic bending field in a high-energy accelerator (in which case the emission is of synchrotron radiation) or a Coulomb field in a nucleus (*Bremsstrahlung*) or a field generated by the image charges on a metal lattice (Smith-Purcell effect). Finally, electromagnetic radiation can be produced by causing a beam of electrons to move in a medium (transparent for this radiation) at a velocity greater than that of light in the medium so that the beam can generate the momentum required to satisfy the conservation laws (Čerenkov effect).

It could be argued that under these circumstances the electron is no longer free, but this is really a question of definition. We shall apply the term 'free' from now on to any electron not bound to a nucleus in a stationary state. The remainder of this article will concentrate on radiation in a magnetic field, because the operation of the free electron laser (FEL) developed at Stanford is based on this principle. It is interesting to note, however, that lasers have recently been produced which operate with free electrons in the millimetre wavelength range which are based on the Smith-Purcell effect (Orotron). Coherent absorption by the inverse Čerenkov effect has also been observed during experiments as a by-product of stimulated Čerekov radiation.

A. Renieri, D.Sc.

Was born in 1945 at Certaldo, Italy, and is a physics graduate of the University of Rome. In 1971 he joined the Frascati centre of the *Comitato Nazionale per la Ricerca e per lo Sviluppo dell' Energia Nucleare e delle Energie Alternative*, initially investigating theoretical problems related to the dynamics of particle beams in high energy accumulators, attached to a group using the Adone machine. In 1976 he transferred to the Laser Division and in 1982 to Applied Physics, where he is involved with quantum optics and particularly with theoretical and experimental problems of free electron lasers.

EURO-ARTICLE.

(see page ii)

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Synchrotron radiation

The generation of radiation by charged particles moving in a magnetic field was first achieved in the 1940s when the first high-energy electron accelerators (such as the betatron and synchrotron) were built. When D. Ivanenko and I. Pomeranchuk were investigating in 1944 the limits of energy obtainable with a betatron they came to the conclusion that the output from a charge moving in a magnetic field increases rapidly with energy and decreases with the particle's mass. It was clear, however, that appreciable synchrotron radiation could be obtained only from ultra-relativistic electrons and positrons ($E \gg m_0c^2$, where E and m_0 are the energy and mass of the particle and c is the velocity of light in a vacuum).

An interesting fact is that recently weak proton radiation has been observed in the visible range (energy level approximately 300 GeV) in the SPS protosynchrotron at CERN in Geneva.

A typical feature of synchrotron radiation is its considerable band width. To illustrate this more clearly figure 1 shows the spectral distribution of synchrotron light as a function of ω/ω_c, where ω is the frequency of the radiation emitted and ω_c the '*critical frequency*' dependent on the curvature radius of the trajectory and the energy of the electron.

As shown in figure 1, radiation stretches continuously from the low frequencies to those approaching the critical frequency ω_c. In the case of ultrarelativistic electrons this frequency is extremely high. To give an example, between 100 MeV and 1 GeV the radiation emitted ranges from the visible frequency ($\omega_c = 3 \times 10^{15}$ Hz) to hard X-rays ($\omega_c = 3 \times 10^{18}$ Hz) for radii of curvature of approximately 1 metre.

This considerable bandwidth is due to the dynamics of synchrotron radiation. To give a clearer illustration of this point, which is particularly important to us as it is closely linked to problems associated with the free-electron laser, figure 2 shows the emission process for an electron moving in a circular orbit. The radiation emitted due to the acceleration induced by the magnetic field is concentrated forwards in the direction of movement in a small cone with the following aperture:

$$\theta \simeq \frac{m_0c^2}{E} \quad (1)$$

For ultrarelativistic electrons this aperture is very small. Consequently an observer standing some distance away on the orbit plane will see only the light emitted by a small portion l_c of the trajectory (see figure 2) subtended by

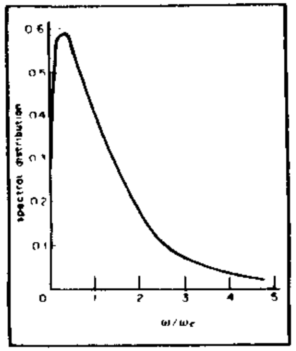

Figure 1 Spectral distribution of electromagnetic radiation emitted by a high-energy charged particle moving in a uniform magnetic field (synchrotron radiation). The abscissa shows the ratio between frequency emitted (ω) and critical frequency (ω_c).

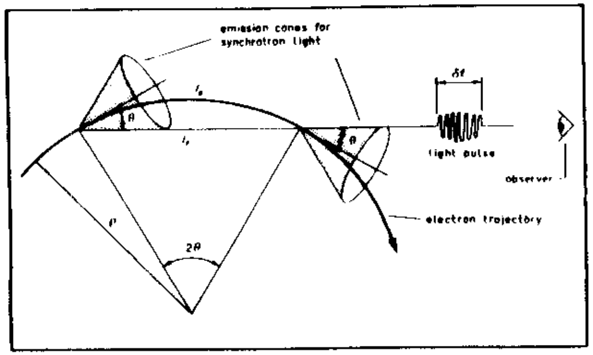

Figure 2 Process of synchrotron radiation in a uniform magnetic field. Light is emitted forward within an aperture cone given by equation (1). An observer at the height of the orbit plane sees the radiation emitted by the particle only within arc l_e subtended by an angle equal to twice the value of the emission angle. Duration of the light pulse (δt) is thus given by the difference in passage times of the particle on arc l_e and the photons on the chord l_f subtended by l_e.

an angle twice that of the emission cone aperture represented by equation (1). The duration δt of the light pulse seen by the observer is determined, as will be readily understood, by the difference between the passage times of the electron on arc l_e and the photons on chord l_f subtended by l_e (see also figure 2) and is also extremely short. The substantial bandwidth of the synchrotron radiation is due to the short duration of the light pulse. From Fourier analysis of a wave train of finite length it can be seen that the radiation spectrum emitted extends to frequencies as high as the inverse of δt:

$$\omega \sim \frac{1}{\delta t}$$

This frequency is the critical frequency (ω_c) referred to earlier (figure 1).

Synchrotron radiation from a magnetic undulator

Synchrotron light is now widely used in many areas of research (basic and applied physics, chemistry, biology, etc.). Its considerable bandwidth extends its scope of application by providing a light beam with a wide range of frequencies (from infrared to X-rays) but at the same time has the effect of limiting output per unit of available frequency. In order to improve this parameter H. Motz proposed in 1951 the irradiation of an electron beam in a static periodic magnetic field (magnetic undulator). A field of this type can be produced, for example, by a sequence of alternate magnetic dipoles, as shown in figure 3. Under the influence of this field the electron does not follow a circular trajectory but oscillates along the axis of the magnet. If the intensity and period of the magnetic field are selected in such a way that the angle of deviation of the trajectory from the axis is always less than the angle of cone aperture within which the radiation is emitted, an observer on the axis of the undulator (figure 3) would see the light emitted along the entire length of the trajectory and not merely from a small fraction of it. This experimental arrangement produces what is commonly known as 'undulator operation'.

The light pulse duration is much longer than that of the example considered in the previous paragraph (circular trajectory). Consequently the emission band is considerably narrower and its relative width is inversely proportional to the number N of undulator periods:

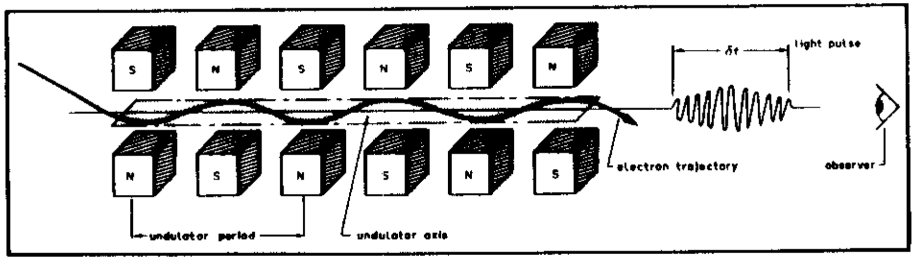

Figure 3 Diagram of the magnetic undulator, in which the field is generated by a series of alternate magnetic dipoles. S and N denote the south and north alternation of the magnetic dipoles. The trajectory of a charged particle oscillates about the axis of the undulator. By controlling period and magnetic field intensity the angle of deviation of this trajectory from the magnetic axis is less than the width of the emission cone. Consequently an observer on the axis of the undulator would see the radiation emitted along the entire length of the magnet. The duration δt of the light pulse is thus considerably greater than that associated with synchrotron radiation in a homogeneous field (for the same magnetic field and electron energy).

$$\left|\frac{\Delta\omega}{\omega}\right|_n = \frac{1}{2N} \qquad (2)$$

The significance of Eq. (2) is obvious. The longer the undulator (i.e. the larger N), the longer will be the duration of the light pulse and the narrower the bandwidth. There is a lower limit to the bandwidth due to the quality of the electron beam. In fact an inhomogeneous widening of the spectrum occurs which is a function of emittance (essentially given by the product of transverse dimension multiplied by angular divergence) and the dispersion in energy of the particle.

This widening is similar to the Doppler widening which atoms or molecules undergo during emission. The theoretical features of the radiation emitted in the undulator was studied by D. F. Alferov, Y. A. Bashmakov, and E. G. Bessonov in 1973.

Figure 4 (Graph a) shows the light spectrum radiated along the axis of the magnet, in a homogeneous line condition. The spectrum is symmetrical about the central frequency ω_0, the dependence of which on the energy E of the particle and on the magnet's parameters can be obtained from purely physical considerations. Application of the Lorentz equation shows that in the electron's reference system the static field of a λ_q period undulator (figure 3) is very similar to an electromagnetic wave with the following frequency

$$\omega' = \frac{2\pi c}{\lambda_q} \times \frac{E}{m_0 c^2} \qquad (3)$$

which is propagated in the opposite direction to that of the electron. The merging of the undulator field with an equivalent electromagnetic wave (Weizacker and Williams virtual photon method) improves with the energy level of the electrons. This wave is scattered by the Compton effect and the photons scattered will have the same frequency as the incident photons. The back-scattered light in the laboratory frame undergoes a Doppler shift towards the higher frequencies. The frequency of this radiation, which is the undulator synchrotron radiation, can thus be obtained by the following equation (for ultrarelativistic electrons)

$$\omega_0 \sim 2\left[\frac{E}{m_0 c^2}\right]\omega' \sim \frac{4\pi c}{\lambda_q}\left[\frac{E}{m_0 c^2}\right]^2 \qquad (4)$$

Band width (Eq. (2)) can be obtained by taking into account that it must be equal to that of the incident radiation which is composed of a wave train of N periods.

By continuing the analogy with the Compton scattering, the polarization of the radiation generated can also be established and it will be the same as

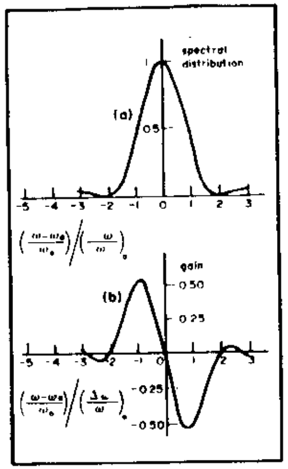

Figure 4 Graph a shows the spectral distribution of the electromagnetic radiation emitted at angle zero along the axis of an undulator. The abscissa shows in units of width of the homogeneous frequency band (cf. equation 2), the difference between the frequency emitted ω, and the central frequency ω_0, as produced by equation (5). Graph b shows the free electron laser gain as a function of frequency. The abscissa shows the same quantity as shown in Graph a. The gain is proportional to the derivative of spectral distribution (Graph a).

that of the incident wave. For example, in the case of the undulator shown in figure 3 linear polarization occurs at right angles to the magnetic field.

For a more accurate determination of central frequency ω_0 allowance has to be made for the energy associated with the transverse movement of oscillation. This involves a small correction to equation 4, which now becomes

$$\omega_0 = \frac{4\pi c}{\lambda_q}\left[\frac{E}{m_0 c^2}\right]^2 \frac{1}{1+k^2} \qquad (5)$$

where K, known as the undulator parameter, is linked to the average quadratic magnetic field B and to period λ_q by the following equation:

$$K = \frac{B\lambda_q}{2\pi m_0 c^2} \qquad (6)$$

Parameter K is extremely important for the definition of the properties of the radiation emitted. In particular, the maximum angle of deviation of the electron's trajectory from the magnetic axis is given by

$$\theta_{max} = k \times \left[\frac{m_0 c^2}{E}\right] \qquad (7)$$

for which reason the operation of the undulator ($\theta_{max} \leq \theta$, cf. Eq. (1)) is obtained by K ≤ 1.

As can be seen from equation (5) the frequency of the radiation produced can be varied by altering the energy of the electrons, the period, or the magnetic field of the undulator. With λ_q = 10 cm and K ~ 1, for example, the light emitted ranges from infrared to ultraviolet when the energy of the electrons is between 10^2 and 10^3 MeV. Under these conditions by using a 5 m long undulator (N = 50) the relative width of the homogeneous band (Eq. (2)) is approximately 1 per cent.

The first undulator, which was based on permanent magnets, was built by H. Motz, W. Thon, and R. N. Whitehurst in 1953. Its main features were as follows: λ_q = 4 cm, L = 50, cm B = 3.9–5.6 kGs, where L is the length of the undulator.

Using the electron beam produced by the Stanford linear accelerator, first operated a short while before, they generated, in accordance with the theory, radiation in the range between green (λ = 550 nm) and blue (λ = 340 nm) for electron energy levels of between 95 and 120 MeV.

Using the same equipment but with a lower-energy electron beam (3–5 MeV) this research team succeeded in generating coherent radiation in the millimetre wavelength range from a number of electrons bunched in packets, the size of a packet being comparable to the wavelength emitted. Under these experimental conditions the electrons actually emit in phase together and consequently the intensity of the radiation, instead of being proportional to the total number of electrons N, is proportional to N^2. The output observed was approximately 1 watt, or some 6 orders of magnitude greater than that obtainable with a non-modulated beam. The authors also indicated that this method was unsuitable for shorter wavelengths and there was no equipment available capable of bunching electrons into packets of less than 1 millimeter. Later, we shall see that the FEL offers precisely this possibility.

In the past few years a considerable number of magnetic undulators has been fitted to electron storage rings in order to produce sufficiently monochromatic tunable synchrotron radiation. In the undulator (electromagnetic) fitted on the Adone storage ring at the laboratories of the Italian National Nuclear Physics Institute (INFN) in Frascati the magnet has three periods (λ_q = 65.4 cm), corresponding to a homogeneous bandwidth of approximately 17 per cent (cf Eq. (2)). The system can operate with a very strong magnetic field on the axis (up to 18.5 kGs), and in this configuration it is used as an X-ray source. For weaker magnetic fields (less than 200 Gs) the magnet operates as an undulator (K≤1). With electrons with energy levels of 500–700 MeV, visible spectrum radiation is produced.

Stimulated Compton scattering
In 1968 R. H. Pantell, G. Soncini, and E. Puthoff put forward the idea of using stimulated Compton scattering to generate coherent radiation which could be easily tunable on a wide spectrum of frequencies by varying the energy of the electrons. A simplified description of this procedure was given by E. Schrödinger as early as 1927, while in 1933 P. L. Kapitza and P. A. M. Dirac proposed an experiment to observe stimulated Compton scattering from non-relativistic electrons.

On the basis of the proposal put forward by Pantell and his collaborators, V. P. Sukhatme and P. A. Wolff calculated in 1973 the gain for this type of laser and came to the conclusion that with the electron beams and electromagnetic radiation sources available at that time the gain for stimulated Compton scattering was too low compared with typical losses for resonant cavities operating in the infrared and visible ranges for a laser oscillator to be worth building.

In the meantime, however, J. M. J. Madey had established in 1971 that using a static magnetic undulator instead of a real electromagnetic radiation source (a klystron, for example) it was possible to obtain sufficient gain to produce a laser effect. This is explained by the fact that the power density of the radiation corresponding to the undulator can be extremely high compared with that of a real wave, because it is possible to generate experimentally very strong static magnetic fields. The undulator built by Motz and collaborators, for example, was the equivalent of a radiation with a wavelength of λ = 8 cm and an output density of between 1 and 2 GW/cm^2, some orders of magnitude greater than anything which could be obtained with a conventional source for that wavelength. The dependence of gain on the operating frequency of a laser based on stimulated Compton scattering (or alternatively on stimulated synchrotron radiation in an undulator) is very peculiar (figure 4 (Graph b)). Instead of following the spectral distribution of the spontaneous radiation (Graph a in figure 4) as in conventional lasers, gain is proportional to its derivative. Such behaviour is due to the nature of the interaction which is based on a scattering process and not a process of radiation from bound states.

As Graph b in figure 4 shows, the gain for this particular type of FEL is zero when the frequency is the same as central frequency ω_0 when emitted

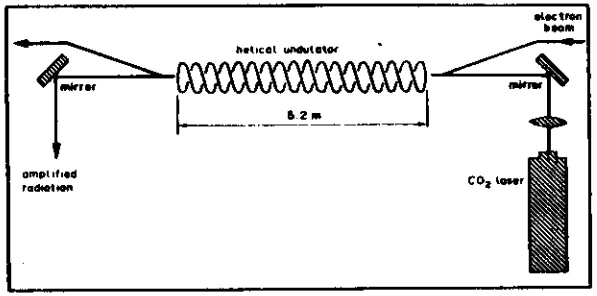

Figure 5 Diagram of the Stanford FEL amplifier. The electron beam produced by the superconducting linear accelerator is passed along the axis of a superconducting helical undulator. The radiation for amplification is generated by a TEA CO_2 laser.

spontaneously. On the other hand, positive gain is obtained whenever the wave to be amplified is of a frequency less than ω_0, and there is negative gain if the reverse is the case. Maximum amplification occurs in the area where the spontaneous emission spectrum curve rises most sharply, while the positive part of the gain curve is equal in width to that of the homogeneous band. It is easy to estimate, and subsequently confirm by more accurate calculations, the maximum power that can be transferred from the electron beam to the laser beam. If allowance is made for the fact that the radiated frequency is dependent on the energy levels of the electrons (cf Eq. (5)), the maximum energy obtainable from the electrons themselves is that which induces a shift of the operating frequency to a level off the gain graph. Consequently the maximum efficiency obtainable, η max., defined as the ratio between energy transferred to the laser beam and the initial energy level of the electrons, is given by the relative width of the gain graph:

$$\eta \max \sim \frac{\Delta\omega}{\omega} = \frac{1}{2N} \qquad (8)$$

First observation of stimulated synchrotron emission
The shape of the gain curve for stimulated synchrotron emission in a magnetic undulator (Graph G, figure 4) was confirmed experimentally by the first test carried out at Stanford by L. R. Elias, W. M. Fairbank, J. M. J. Madey, H. A. Schwettman, and T. I. Smith in 1976. The experimental equipment is shown in diagrammatic form in figure 5. A superconducting magnet in the form of a double helix wound round a copper tube was used as the undulator. Figure 6 shows a photograph of a number of the magnetic periods. In the two helical coils current flows in opposite directions and the magnetic field generated is perpendicu-

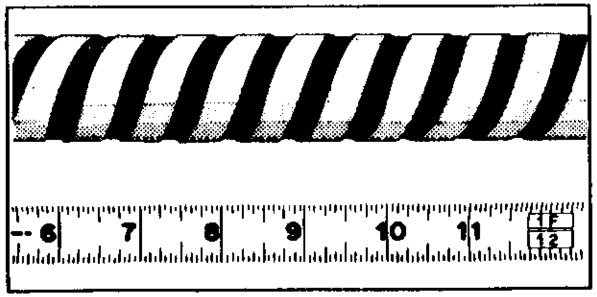

Figure 6 Some periods of the superconducting double helical undulator built at Stanford. In the two helixes the current passes in opposite directions, and the magnetic field generated is thus perpendicular to the axis of the undulator and rotates with a period corresponding to the period of the helix.

lar to the axis of the undulator and rotates at a period equivalent to the period of the helix.

According to Weizacker and Williams' approximation, this type of field corresponds to an electromagnetic wave with circular, right-hand polarization. The main features of the undulator are shown in Table 1.

TABLE 1 THE SUPERCONDUCTING HELICAL UNDULATOR OF STANFORD UNIVERSITY

Period (cm)	3.2
Length (m)	5.2
Width of homogeneous band (%)	0.3
Magnetic field on the axis (kGs)	2.4

A beam of electrons produced by the Stanford superconducting linear accelerator with an energy of E = 24 MeV and a peak current I_p = 70 mA and a beam of infrared light with a wave length of λ = 10.6 μm and an output density of 1.4 × 10^{5}W/cm^2, generated by a carbon dioxide laser (TEA CO_2 laser (TEA standing for transversally excited at atmospheric pressure)) are passed along the axis of the magnet.

Figure 7 shows the spontaneous radiation output (Graph a) and the gain (Graph b) as a function of the energy of the electron beam at the CO_2 laser wavelength (~ 10.6 μm). The experimental graphs confirm the theoretical estimates (figure 4). It is worth noting that the preferred method was to vary the energy of the electrons, as this operation, which corresponds to varying the frequency of the laser (cf. Eq. 5) is the easier operation under experimental conditions.

The maximum measured gain was approximately 7 per cent per passage, which is sufficiently close to the theoretical estimate. This gain corresponds to a stimulated output emission of approximately 4 × 10^{3}W, compared with the spontaneous radiation (that is, radiated without an incident laser beam) which was about 4 × 10^{-6}W. The increase in output was thus of some nine orders of magnitude. Lastly it was established that only the radiation with the same polarization as the undulator is amplified: zero gain was measured for radiation with circular left-hand polarization.

The full evaluation of the experimental data involved a considerable amount of work. In particular, it became clear that the stimulated Compton scattering can be considered as two distinct phases. In the first instance, the action of the laser beam and undulator beam modulates the energy of the electron beam and this energy modulation is then transformed into density modulation at the same wavelength as that of the laser: in other words, there is coherent radiation which intensifies the existing laser field.

At this point a comparison with the millimetre wave source built by Motz and collaborators referred to earlier may be of interest. In that experiment the density of the electron beam was modulated as it entered the magnet. In the FEL, on the other hand, the entire process (modulation and emission) automatically occurs in the undulator, which allows laser operation at wavelengths ranging from submillimeter to ultraviolet.

First operation of an FEL as an oscillator
In 1977, one year after the first amplification experiments, D. A. G. Deacon, L. R. Elias, J. M. J. Madey, C. J. Ramian, H. A. Schwettman, and T. I. Smith built the first FEL oscillator, referred to at the beginning of this article.

The experimental device, which is depicted in figure 8, uses the helical undulator successfully tried in the amplification experiments (figure 6 and Table 1). The electron beam is still the same one produced by the Stanford superconducting accelerator, but this time the energy level is higher (E~43 MeV). Consequently, the operating wavelength is shorter (λ~3.4 μm). Radiation is initially produced by spontaneous synchrotron radiation and then, reflected by the two mirrors located at the ends of the undulator, it is amplified in the course of subsequent passes with the electron beam inside the magnet. The main characteristics of the electron and laser beams, updated by latest (1981) experimental data, are shown in Table 2.

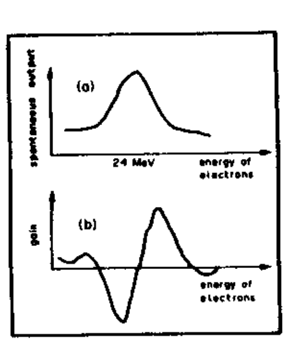

Figure 7 Radiation output by spontaneous emission (Graph a) and gain (b) measured (with the equipment built at Stanford) at the wavelength of the TEA CO_2 laser (λ~ 10.6 μm) as a function of the energy of the electron beam.

TABLE 2 MAIN FEATURES OF THE STANFORD FEL

ELECTRON BEAM (SUPERCONDUCTING LINEAR ACCELERATOR)		
Energy (MeV)		43
Energy spread (%)		5×10^{-2}
Emittance (mm × mrad)		4×10^{-2}
Peak current (A)		1.3
Average current (μA)		60
LASER BEAM		
Wavelength (μm)		3.3
Line width (nm)	2.5	6.6
Average output (W)		5
Peak output (kW)		130

The effect of the laser is most apparent if the outputs above-threshold (gain greater than losses) and below-threshold (gain less than losses) are compared. The ratio between these two levels is extremely high (~ 10^8). Another important parameter is the narrowing of the emission line from $\delta\lambda$~36 nm (below-threshold) to $\Delta\lambda$~8 nm (above-threshold) as shown in the spectrum in figure 9. The width of the spontaneous emission line (lower graph in Figure 9) is due mainly to the homogeneous widening resulting from the excellent characteristics of the electron beam (slight spread of energy and emittance) (Table 3).

The width of the laser line is determined by the variation with time of the electron beam. This is composed of a continuous train of electron packets with a duration of τ~3.2 ps at approximately 84.7 ns intervals. This interval was chosen in order to be approximately the same as the time taken by the light to travel back and forth in the optical cavity

The radiation moving back and forth in the cavity and the subsequent packets of electrons are thus synchronized. A sort of mode-locking device is thus obtained. The result is that the laser radiation is no longer continuously distributed but grouped into light pulses, the duration of which is approximately the same as that of the electron packet. The width of the laser line under these conditions is inversely proportional to the duration of the micropulse

$$\Delta\omega \sim \frac{2\pi}{\tau} \sim 1500 \text{ GHz} \qquad (9)$$

which in terms of wavelength corresponds to $\Delta\lambda$~9 nm and confirms the experimental results (figure 9).

Table 2 shows the energy transfer efficiency from the electron beam to the laser beam, as represented by the following equation:

$$\eta = \frac{P_L(W)}{I(A) \times E(eV)} \sim 0.2 \text{ per cent} \qquad (10)$$

Where I and E are the average current and energy of the electron beam and

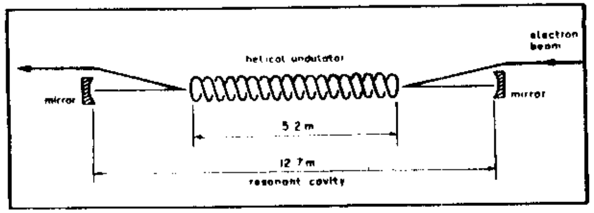

Figure 8 Operation diagram of the Stanford FEL oscillator. The radiation is produced by spontaneous synchrontron irradiation and then reflected by the two mirrors located at the ends of the undulator. It is amplified during subsequent passes with the electron beam inside the magnet.

P_l is the average output of the laser. These results are in complete harmony with the theoretical limit given by the homogeneous bandwidth (cf. Eq. (8)), which for the Stanford FEL is approximately 0.3 per cent (Table 1).

At the beginning we spoke of evidence of the production of laser light, intending this rather general term to mean coherent light. A theoretical study of the process by R. Bonifacio, G. Dattoli, A. Renieri and F. Romanelli, in 1980, confirmed that FEL radiation shows coherence properties similar to those shown by the light from conventional lasers.

The FEL in storage rings

Amplification experiments have recently been carried out at Orsay in France, at Frascati in Italy and at Novosibirsk in the USSR. In all these cases the equipment used an electron beam circulating in a storage ring. A diagram of the FEL storage ring configuration is given in figure 10. After they have given off energy to the laser beam, the electrons are re-accelerated by the machine's radiofrequency system and subsequently re-injected into the undulator to interact again with the radiation beam. Ultimately, there is a continuous transfer of energy from the storage ring accelerator system to the laser beam via the electron beam. Contrary to appearances, this process is not more efficient than the single-pass FEL system (Stanford model), where the electron beam is trapped in a beam dump after it has given off a small portion of its energy to the laser beam. The reason for this is that the successive interactions between the electron beam and the laser beam continuously increase the electron energy spread (that is, they 'heat up' the electron beam). This process causes the spontaneous emission line to be widened inhomogeneously and lowers the system's gain to the point where it becomes less than losses from the resonant cavity, thus terminating the laser process.

The only possibility of limiting this effect involves synchrotron irradiation in the bending magnets of a storage ring. The greater this radiation, the more efficient the cooling of the electron beam becomes since the output obtainable from an FEL operating in a storage ring is linked to the output radiated (P_s) by sychrotron emission. It can be demonstrated (G. Dattoli and A. Renieri (1980)) that the maximum laser output is described by the following equation:

$$P_{max} \sim \left[\frac{\Delta\omega}{\omega}\right]_0 P_s \qquad (11)$$

In this case $(\Delta\omega/\omega)_0$ is the homogeneous band width. Maximum efficiency is thus described by:

$$\eta_{max} \sim \frac{P_{max}}{PN} \sim \left[\frac{\Delta\omega}{\omega}\right] \simeq \frac{1}{2N} \qquad (12)$$

where N is the number of periods in the undulator. This equation is consonant with that already obtained for the single-pass FEL (8).

Let us now describe in more detail some of the experiments mentioned earlier. The characteristics of the Orsay amplifier are given in Table 3. The magnet is in the form of superconducting helixes which create a periodic field parallel to the plane of the apparatus; the polarization of the wave generated is thus linear. A maximum gain per pass through the magnet of 4 × 10^{-4} was registered (at a wavelength of = 488 mm). This extremely low value corresponds to the limit for losses from a typical resonant cavity operating at that wavelength.

The slight gain on the FEL at Orsay is due, among other things, to the low number of magnetic periods (N = 23). One of the greatest hindrances to the operation of an FEL in a storage ring is in fact the absence of sufficiently long straight sections. To overcome this difficulty, N. A. Vinokurov and A. N. Skrinsky proposed a variant to the traditional free electron laser in 1977. This device, which the two authors called an optical klystron, is shown in figure 11. It is composed of two undulators each with an equal number of periods, separated by a triplet of bending magnets of inverted polarity so that total deflection is zero. The FEL process can thus be divided into its three separate stages. In the first undulator the electron beam is energy-modulated; this energy modulation is transformed in the magnetic triplet into density modulation. Finally, in the last undulator the process of coherent radiation occurs. This configuration is much more efficient than the traditional one, in that for the same length the density modulation is much more intensive due to the dispensive characteristics of the magnetic triplet (electrons with different energy levels describe orbits of different lengths). The Novosibirsk FEL operates on the basis of this principle. The optical klystron was fitted to the VEPP-3 storage ring and the first spontaneous emission and gain measurements were carried out using an HeNe laser which confirmed the theoretical estimates. Finally an optical klystron FEL oscillator is now in operation at Orsay.

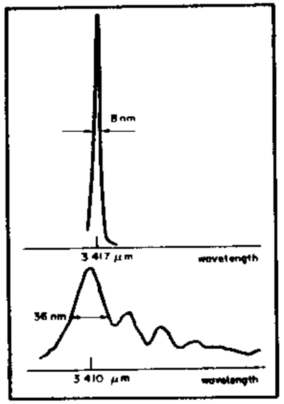

Figure 9 Spontaneous emission line (lower graph) and laser line (upper graph) for the Stanford FEL (cf figure 8 and Table 2).

TABLE 3 MAIN FEATURES OF THE ORSAY FEL AMPLIFIER SUPERCONDUCTING UNDULATOR

Period (cm)	Length (cm)	Homogeneous band width (%)	Maximum magnetic field on axis (kGs)
4	94	2	4

Electron Beam (ACO)		*Laser Beam (argon)*	
Energy (MeV)	Average current per electron packet (mA)	Wavelength (nm)	Output density (W/cm²)
150	10–20	488.0 514.5	1.6 × 10^7

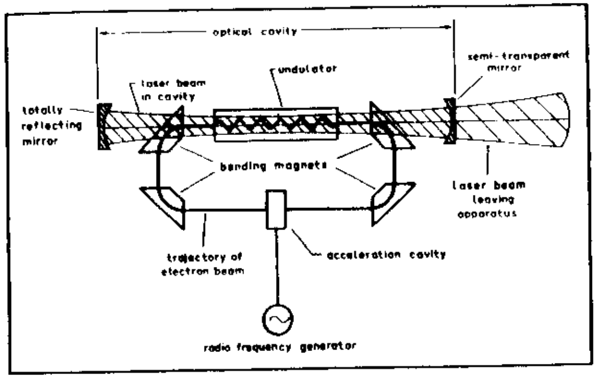

Figure 10 Operating diagram for a FEL in a storage ring. After they have given off energy to the laser beam in the undulator, the electrons are reaccelerated by the machine's radiofrequency system and made to interact again with the radiation beam. The particles thus circulate continuously in the ring and transfer energy from the radiofrequency system to the laser beam.

The FEL (Raman operation)

At the same time as the work on FEL apparatus using high-energy electron beams (E>10 MeV) and low current (U~1·10²A) was in progress laser sources operating in the millimetre wavelength range, which use low-energy electron beams (E~1–2 MeV) and high current (I~10–20 kA) produced by accelerators such as the Marx generators and linear induction accelerators, were also undergoing development. In these machines there is considerable interaction between the charged particles. In particular, the electromagnetic radiation and the undulator field can excite collective oscillation modes in the electron beam (plasma waves). The frequency of the radiation generated can no longer be calculated simply on the basis of equation (5) which essentially reflects the Doppler shift of the simulated undulator wave. Instead, it is shifted towards the low frequencies owing to energy absorption on the part of the plasma oscillation modes.

These radiation sources have been termed Raman FELs in view of the similarity to the Ramnan light diffusion process by molecules. The FELs operating at low density and high energy (the Stanford model) are accordingly sometimes called Compton FELs.

The first Raman FELs were built at the Naval Research Laboratory (NRL) in Washington, Columbia University in New York; the laboratories of the TRW in California; and the Institute of Nuclear Physics, Tomsk, USSR. A diagram of the Raman FEL built by the NRL is shown in figure 12 as an example of a spontaneous radiation amplifier.

The large structure to the left is the accelerator for intensive electron beams (VEBA, E = 1÷2 MeV, I = 1–100 kA, pulse duration ~50 ns). The electron beam is passed into a double-helix pulsed undulator. This type of undulator has a 3 cm period, a length of 1 m, and a maximum field of 4 kGs. This apparatus has been used to generate millimetre and submillimetre radiation with an output of ~1÷10 MW.

The FEL: special features and future prospects

To understand fully why the FEL aroused so much interest when it first appeared, one must take a close look at its main features: it can be modulated, it has a good line width, it is efficient, and it can be boosted to high average output levels. Let us also review the enormous range of activities at international level aimed at producing new FEL sources specifically designed to optimize particular operating parameters for specific purposes.

Tunability. The free electron laser's most striking characteristic is without doubt its ability easily to accommodate changes in its operating frequency. Whereas in the case of lasers based on emission stimulated by atoms or molecules this parameter is determined by the difference in energy between the states affected by the transition, the FEL's frequency can be varied by changing the energy of the electron beam, the period and the magnetic field of the undulator (cf. Eq. (5)). As a result of this the FEL can potentially cover continuously the entire spectrum from millimetre waves to ultra-violet waves. The importance of this type of laser is most obvious where tunable sources are not available, for example in the far infra-red and in the ultra-violet range. It is less important in the visible range, where the dye lasers can cover the entire spectrum with excellent results.

The problem of extending the operating range of the FEL to include very short wavelengths (λ~100 nm) is one which deserves special attention. In the very short wavelength range the reflectiveness of the mirrors is greatly reduced (usually by something approaching 50 per cent). Consequently, to build an

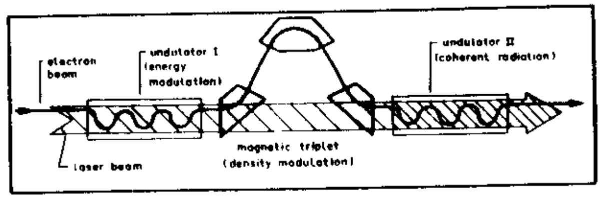

Figure 11 Operating diagram for the optical klystron. In the first undulator the energy modulation of the electron beam is obtained and this is then transformed in the magnetic triplet into powerful density modulation. In the second undulator the coherent radiation process finally occurs.

FEL oscillator operating in that range of the spectrum, very high gain will be needed, and this can be obtained only with very high peak currents $(I \sim 10^{2} - 10^{3}$ A). Such high currents can be readily obtained in the high-energy storage rings and these machines would thus appear to be the best sources of electrons for FELs operating in the far ultra-violet.

There are currently many projects under way aimed at building free electron lasers on storage rings. Earlier, we described the experiments conducted at Orsay and Novosibirsk. At the present time experiments on FEL amplification and oscillation are being conducted at the Brookhaven laboratories in the United States, where a synchrotron light storage ring will be used to produce laser radiation at wavelengths of 250–450 nm by means of a permanent magnet undulator (period = 6.5 cm, number of periods = 38) and also at INFN at Frascati. In this experiment the electron beam from the Adone ring is used. The undulator is in the form of an electromagnet, the main features of which are shown in Table 4, together with the main feaures of the electron beam. Initially, experiments on radiation amplification produced by an argon laser with a wavelength of 514.5 nm has been carried out.

The gain per pass is approximately 10^{-4}. At a later stage laser oscillator will be built both in the traditional way and in the high-gain configuration of the optical klystron type.

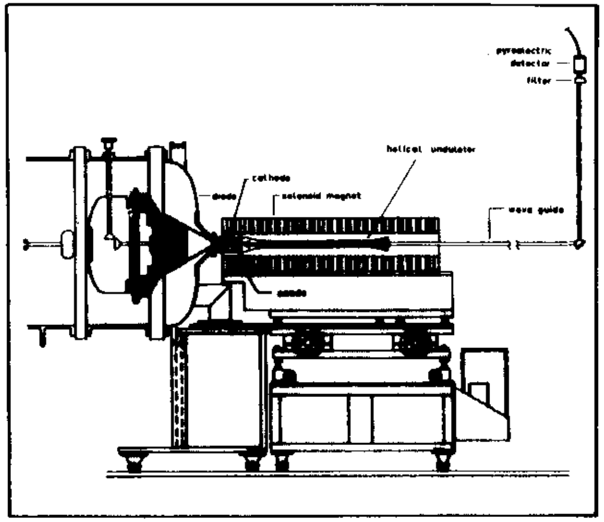

Figure 12 Diagram of the single-pass spontaneous radiation amplifier built at the Naval Research Laboratory, Washington, DC. The electron beam produced by the VEBA accelerator (device on left) is passed into the helical undulator shown at the centre of the photograph. A solenoid magnet is used to focus the electrons inside the undulator. On the right is the detector for the radiation produced.

Line width. The variation with time of the laser beam is closely related to that of the electron beam. Consequently, as was demonstrated in connection with the description of the Stanford experiments, if the electrons are bunched in packets the photon beam will also be in the form of a pulse train having a duration approximately the same as that of the electrons. This situation occurs when the acceleration is provided by systems using resonant cavities at radio frequencies, which is the case of linear accelerators, microtrons and storage rings. Under these circumstances the duration of the lighty micropulse is very short (normally between 10^{-12} and 10^{-9} s). This leads to a relatively large line width, as shown by equation (9).

A recent proposal (currently being developed at the University of California in Santa Barbara) was for an FEL source in the far infrared ($\lambda \sim 100$-400 μm) using a continuous electron beam with an energy of 3 MeV and current density of 16 A cm^{-2} produced by an electrostatic generator. Under these conditions the line width of the laser is much less than that of sources which use radiofrequency accelerators. An interesting aspect of the experiment is the recovery of the electron beam after the FEL interaction in the undulator. This aspect of free electron laser technology, which determines the overall efficiency of the system, will be considered in more detail in the next section.

Efficiency. As was seen earlier, only a small fraction of the electron beam's energy is transferred to the laser beam. A number of ideas have recently been put forward with a view to improving the efficiency of the FEL source. They fall into two distinct groups. The first group comprises the systems which recover the residual energy from the electron beam, while the second group concentrates on improving the efficiency of the energy transfer between electrons and laser beams.

The FEL project under development at the University of California belongs in the first category. In this apparatus, the electron beam is decelerated after passing through the undulator and its energy and charge are for the most part recovered.

In the second group we find the designs which use special, variable-parameter undulators. In these systems the period and the magnetic field are changed along the undulator so as to cancel the frequency shift due to energy losses from the electron beam. Theoretical estimates predict an energy transfer efficiency between electrons and photons of some 50 per cent. Apparatus for the experimental verification of the validity and applicability of this model has been developed successfully at the Los Alamos Laboratories of Mathematical Science Northwest and TRW in the United States.

TABLE 4 PRINCIPAL PARAMETERS FOR THE FEL SOURCE BEING BUILT AT THE ITALIAN NATIONAL NUCLEAR PHYSICS INSTITUTE AT FRASCATI

Undulator (electromagnetic)				Electron Beam (Adone)	
Period (cm)	Length (m)	Homogeneous Band width) (%)	Max. magnetic field on axis (kG)	Energy (MeV)	Average Current per electron packet (mA)
11.6	2.32	2.5	4.459	610	100

TABLE 5 MAIN PARAMETERS OF THE FEL SOURCES UNDER DEVELOPMENT AT THE ENERGY RESEARCH CENTRE IN FRASCATI

Undulator (SmCo permanent magnets)				Electron beam (microtron)				
Period (cm)	Length (cm)	Homogeneous band width (%)	Maximum magnetic field on axis (kGs)	Energy (MeV)	Average current (mA)	Peak current (A)	Current pulse duration (μs)	Repetition frequency (Hz)
5	2.25	1.1	3	20 30	350 250	6.5 4 5	12	150

Boosting to high output levels. The FEL oscillator at Stanford produced a laser beam with an average output of around 5 W (Table 2). It should be remembered, however, that this result was obtained with a very low average current (~60 μA). Using a conventional linear accelerator as an electron source it is possible, however, to produce average currents in the 10 to 100 MeV range that are ten times greater than that obtained at Stanford. The use of electron beams with these characteristics allows laser beams to be generated which have an average output of some several hundred watts.

As an example, Table 5 shows the major parameters for the FEL oscillator being built at the ENEA's (formerly CNEN) energy research centre at Frascati, which uses a microtron as an electron source. The long-term objective of this project is to build a source which is tunable in the near infrared ($\lambda = 10 - 30$ μm) with an average output of between 50 and 100 W.

Some possible uses for the free electron laser

It is possibly still somewhat premature to discuss in detail the possible applications of the FEL. What is clear is that its major feature—that it can be tuned—renders it an ideal source for photochemistry in general, and isotopic separation by laser in particular.

In addition to this extensive field of application we could also mention two possible uses particularly relevant at a time like the present in which the search for new energy sources appears to be one of the most urgent problems facing our industrial society.

One application concerns the possibility of building high-efficiency amplifiers with variable-parameter undulators. The high laser energies obtainable in this way (~100 – 1 000 kJ) concentrated in very short pulses (~100 ns) make these devices suitable for use as energy production systems based on inertial nuclear fusion by laser.

The second application concerns the potential production (using the Raman FEL sources) of tunable radiation on the 100–1000 μm band with high peak output (100 1000 MW) in pulses lasting ≥ 1 μs and good efficiency (~ 10 per cent). With such apparatus it will be possible to heat plasmas (using cyclotron resonance or its harmonics) in magnetic confinement machines (of the high-field Tokamak type) for triggering the process of controlled nuclear fusion for energy production.

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Book reviews

Assessing the Impacts of Technology on Society. *80 pp. OECD, Paris. 1983. Paperback £4.50*

This book is concerned with the role of technology assessment (TA), and in particular with the way in which that role is perceived to have evolved over the last fifteen years or so. It is not a collection of methodologies, and neither does it present views on how particular technologies have affected society. The author stresses how TA has broadened in scope from being concerned mainly with identifying possible negative effects of technology on the environment or on society, to involving itself more fully with policy analysis and complex technical-social interactions. Problems of embodying TA within existing institutional frameworks are stressed. It is surely correct to identify these problems, rather than the further development of narrowly defined 'techniques', as being of central importance in efforts to improve the state of the art. Much of the discussion is somewhat laboured, however, and this reviewer felt a strong temptation to skip over some of the passages. In addition, the author is somewhat excessively internationalist, one conclusion being that interrelationships between societies are such that '... to hasten the spread of desirable new technologies becomes practically impossible at the national level'. This scarcely accords with recent evidence. Overall, though, a useful contribution.

J. A. Clark

In Quest of Telescopes. *By Martin Cohen. Pp. 131. Cambridge University Press and Sky Publishing Corp., Cambridge, Mass. 1983. £8.50.*

This entertaining and well illustrated book is essentially an autobiography. Dr Cohen, a researcher in the field of infra-red astronomy, has worked at a number of the great observatories of the world. He tells his story mainly as a guide to young hopefuls who might wish to follow in his footsteps. Nevertheless, *In Quest of Telescopes* should appeal to any reader with even the remotest interest in astronomy.

The author must be one of the few scientists ever to attempt an autobiography before attaining the age of forty. However, he has produced both a readable and informative piece of work. The book begins with a somewhat nostalgic look at Cohen's early career in England, where he graduated from schoolboy observer to research astronomer at Cambridge. There follows an account of his travels to telescopes throughout the continental United States as well as Hawaii and Chile.

Cohen's story gives a fascinating insight into the sometimes hectic life of an observational astronomer. No doubt some readers will be irritated by his rather flippant style (this remark includes the reviewer!). Still, this is more than compensated by his infectious enthusiasm. It is evident that he has 'immensely enjoyed' his quest for telescopes.

F. R. Stephenson

Old and New Questions in Physics, Cosmology, Philosophy, and Theoretical Biology. Essays in Honour of Wolfgang Yourgrau. *Edited by A. van der Merwe. Pp. 920. Plenum, New York. 1983. $95.00.*

The present work is a Festschrift honouring the memory of the physicist-philosopher Wolfgang Yourgrau, who died in 1979. It comprises 57 papers covering a very wide range of topics mainly in the foundations and philosophy of physics together with a biographical introduction by van der Merwe and a dedication by Sir Karl Popper. The list of contributors is distinguished—Bohm, de Broglie, Barut, Ivanenko, Ludwig, Mandelstam, Bondi, Kastler, North, Synge, and Wisdom to pick a few names more or less at random. The first half of the book is concerned with technical foundational problems in such areas as elementary particle physics, quantum mechanics, general relativity, and cosmology. Together these papers provide the reader with a pretty good idea of the sort of work being done in these fields at the present time. The second half of the book is a rather rag-bag collection of articles on philosophy and history, together with three or four pieces on theoretical biology squeezed in for good measure. The book as a whole is very long and lacks focus, but accurately reflects Yourgrau's own amazing breadth of interest. It is a fitting tribute to a remarkable man.

M. L. G. Redhead

Micro-electronics, Robotics and Jobs. *Pp. 265. OECD, Paris. 1982. Paperback £12.50.*

This latest volume in a series of OECD publications, dealing with the economic effects of new technology, is based on a conference held in October 1981. Most of the first part of the book is taken up by a report by P. Stoneman, N. Blattner, and O. Pastre on the impact of information technologies on productivity and employment. The authors summarise a number of national reports which had by then been produced and point out that the new microelectronic technologies had not shown revolutionary economic effects and were not likely to do so. The authors are reasonably sanguine about compensating employment taking care of labour displacements by microelectronics, but stress the multi-factor causation of economic fortunes.

In his reply to the above report, H. J. Krupp points to the unexplained nature of the current recession and draws attention to the need to deal with both supply and demand economics. One wishes politicians would read these words of wisdom. P. A. David, in his reply, sounds a more worried note. He shows the old dichotomy in economics, going back to Ricardo, between long-run optimism that increased productivity will increase well-being and short-run pessimism about displacement effects of new technology. His own conclusion is that 'concern expressed by workers ... over the shortrun employment consequences of accelerated technological progress is a reaction "not founded on prejudice and error"', to use Ricardo's phrase.

The second part of the book contains four reports on the adoption of robots and similar production technologies in Germany, Sweden, Japan, and France. They range from the highly factual to pure rhetoric but the facts are worth having.

E. Braun

Organic Photochemistry, Vol. 6. *Edited by Albert Padwa. Pp. 458. Dekker, New York. 1983. SFr. 198.*

This series sets out to review recent developments in organic photochemistry, a topic which has seen a vigorous expansion in the last decade or so. This volume is principally concerned with photochemical electron transfer processes, and is diverse and rather recherché in its content. The five chapters cover separate but nevertheless related topics. Photochemical cyclisations to give nitrogen, oxygen, and sulphur heterocycles are discussed by A. G. Schultz and L. Motyka (119 pp. 162 references) while aromatic alkylations initiated by photoinduced electron transfer are reviewed by R. J. Sundberg (55 pp. 76 references). L. M. Tolbert considers at similar length the photochemistry of organic anions, and the photochemical electron transfer reactions of alkenes and related compounds are dealt with by S. L. Mattes and S. Farid (93 pp. 157 references). Finally S. J. Cristol and T. H. Bindel cover the interesting subject of photosolvolysis of carbocations (88 pp. 123 references).

There is a wealth of new chemistry here, much of it admittedly not well understood as yet. The emphases are those commonly found in organic photochemistry—product structure and distribution in photochemical reactions in the liquid phase, mechanism, and preparative aspects. The emphasis from time to time on photochemical redox processes is welcome. Such processes have long been known, and some of them (for example, in photosynthesis) are important in a broader scientific context. Nevertheless they have not been widely thought about in relation to the photochemistry of simple

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