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A MICROWIGGLER FREE-ELECTRON LASER AT THE BROOKHAVEN ACCELERATOR TEST FACILITY

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ABSTRACT

We report the design and status of an FEL experiment at the Brookhaven National Laboratory Accelerator Test Facility. A 50 MeV high brightness electron beam will be utilized for an oscillator experiment in the visible wavelength region. The microwiggler to be used is a superferric planar undulator with a 0.88 cm period, 60 cm length and $K = 0.35$. The optical cavity is a 368 cm long stable resonator with broadband dielectric coated mirrors.

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INTRODUCTION

We present in this report the preliminary design of a Free-Electron Laser (FEL) oscillator experiment in the visible region of the spectrum to be performed at the Brookhaven National Laboratory Accelerator Test Facility (ATF) linac.

The ATF electron linac is expected to provide a high brightness electron beam of 50 Mev, 100 A peak current and a geometric emittance $\epsilon = \sigma_y \sigma_{y'} = 0.06\,\mathrm{mm-mrad}$. The low emittance opens the possibility of a short wavelength laser and the high peak current makes it possible to achieve sufficient gain to obtain saturation of the laser power with a short undulator.

A very attractive feature of the ATF for laser work is the simultaneous availability of a short pulsed CO_2, Nd-YAG and the FEL radiations. This will make possible unique and interesting user experiments.

It can be argued that the wavelength of the radiation and the emittance of the electron beam are related by the following expression: $\epsilon \lesssim \frac{\lambda}{2\pi}$. Therefore, the constraint on the wavelength in order to avoid gain degradation due to emittance is $\lambda \approx 4 \times 10^{-7}$m. The resonance condition $\lambda \approx \frac{\lambda_u}{2\gamma^2}$ on the other hand, suggests that the undulator period λ_u should be about 1 cm, i.e. a micro-undulator. There is a considerable interest in micro-undulators as an avenue for more compact and inexpensive sources of coherent radiation. The reduction in size of the total system comes from both the reduced accelerator length and the optical cavity size.

However, micro-undulators cause (for various reasons) a reduction in both undulator parameter strength (K), and the number of undulator periods (N); and also increase the level of technological difficulties. This is where a high electron beam brightness becomes an important asset as a means of maintaining a reasonable gain and achieving FEL saturation within the macropulse duration.

We expect to get better emittance in the future as the photocathode gun technique is improved. Thus the undulator technology which we would like to use should be such that further reduction of the undulator wavelength can be easily achieved without reaching its technological limit. As a first step we are considering the use of a superferric magnet undulator with a period of 0.88 cm and a total length of $L = 60$ cm.

THEORY

The dynamics of relativistic electrons in the combined static and radiation fields of the wiggler and laser [1], respectively, are governed by the Lorentz force equations with $\vec{B}_M$ the linearly polarized undulator field $\vec{B}_M = B_0\,(0\,,\,\sin k_u z \cosh k_u y\,,\,\cos k_u z \sinh k_u y)\,,$ where $\lambda_u = \frac{2\pi}{k_u}$ is the undulator period. We use $\gamma^{-2} = 1 - \vec{\beta}_\perp^2 - \beta_z^2$ to connect the longitudinal and transverse motions. In the transverse equation of motion, the electric and magnetic laser forces nearly cancel each other when $\gamma >> 1$, therefore the $\vec{x}_\perp$ position of the electrons are solely determined by the undulator field. The orbits consist of the superposition of a fast wiggling motion in the horizontal plane with period λ_u and a much slower betatron oscillation in the vertical plane of period $\lambda_b = \frac{2\pi}{k_b}$ with $k_b = \frac{K k_u}{\sqrt{2}\gamma}$ where K is the undulator parameter defined as $K = eB_0/mc^2 k_u\sqrt{2}$.

The laser field evolution is described by the wave equation with a driving term given by the sum of single-particle transverse currents. Assuming that the optical field varies slowly over an optical wavelength we can use the slow amplitude and phase approximation to neglect the second derivatives in z and t. We have solved these equations in a resonator configuration with a loss factor of 10% at the end of each pass obtaining saturation after $\approx$ 30 passes with a maximum single pass small signal gain $G \approx 0.55$. The electron beam parameters used in this example are shown in Table 1; the undulator properties are summarize in Table 2 and the optical resonator preliminary design is given in Table 3.

Any inhomogeneity in the electron beam contributes a random component to the electron z-velocity (effective energy spread) with the consequence of decreasing the bunching of the electron beam. In order to quantify these effects we examine the small signal gain analytical expression $G \sim \frac{2-\cos\nu_0-\nu_0\sin\nu_0}{\nu_0^3}$, where $\nu_0 = \frac{4\pi N(\gamma-\gamma_{res})}{\gamma_{res}}$ is the resonance parameter and $\gamma_{res} = \frac{\lambda_u}{2\lambda}\left(1+\frac{1}{2}K^2\right)$. The width of this curve is $\Delta\nu_0 \approx \pi$. The condition not to degrade the gain is expressed by securing that the dispersion in ν_0, introduced by energy spread and emittance is smaller or of the order of π.

The energy spread $\frac{\Delta\gamma}{\gamma} \doteq \sigma_E$. can be obtain from the definition of resonant parameter ν_0. We write $\Delta\nu = 4\pi N\sigma_E$ and consequently,

$$\sigma_E \lesssim \frac{1}{4N}$$

Similarly, from the definition of emittance in terms of the electron beam radius and angular spread $\sigma_y(0)^2 = \epsilon\beta^*$ and $\epsilon = \sigma_y(0)\,\sigma_{y'}(0)$ we write $\beta_z \approx 1 - \frac{\left(1+\frac{1}{2}K^2\right)}{2\gamma^2} - \frac{1}{2}k_b^2\epsilon\beta^* - \frac{1}{2}\frac{\epsilon}{\beta^*}$ and the concomitant change in ν is $\Delta\nu_0 = \frac{1}{2}Lk\left(k_b^2\epsilon\beta^* + \frac{\epsilon}{\beta^*}\right)$. The optimal value of the beta function of the electron beam is $\beta^* = \frac{1}{k_b} \sim \frac{1}{2}N\lambda_u$ and therefore the relevant condition on the emittance for no gain degradation is

$$\epsilon \lesssim \frac{\lambda}{2\pi}.$$

THE UNDULATOR

As we have remarked in the Introduction, we plan on using a micro-undulator in this FEL experiment. Our motivation is not just attaining a short wavelength but also developing a compact FEL system based on small, high brightness linac and compact undulators with a broad wavelength coverage.

The micro-undulator is an important ingredient of this approach and there is widespread interest in the development of such devices. While permanent magnet undulators are by far the most common, their typical λ_u is about 2 cm.

Out of the variety of other methods, we have elected to use a super-ferric magnet for the following reasons: Air core magnets have to be pulsed and thus limit the repetition rate of the FEL. A superconducting magnet with a ferromagnetic core provides a stable dc field without recourse to expensive high stability pulsed power supplies. The demands on the superconductor are minimal since the wire is operated at a very low magnetic field.

The disadvantage of this type of magnet is the somewhat limited access to the undulator which must be housed in a cryostat; this also makes the alignment and characterization more difficult. On the other hand the low cost of the undulator and power supply makes up for the cost of the cryostat.

We believe that this technology can be applied to undulators with even shorter period than 0.8 cm. In this type of electromagnet the period can be reduced without affecting the undulator constant K as long as we maintain a constant gap to period ratio, and a constant current. The disadvantage, of course is that as the area of the coil is reduced in proportion to the period squared, we must increase the current density.

As we shall show below, our present design achieves $K = 0.34$ with a current density of 1390 Amp/mm^2. This figure already includes the wire packing and insulation.

To estimate the undulator constant K we can use the following expression [2]

$$K = 8.45 \times 10^{-4}(NI)\left[\frac{1}{\sinh(\xi)} - \frac{1}{\sinh(3\xi)}\right] \quad (1)$$

where (NI) is the ampere turns per coil, $\xi = \frac{\pi g}{\lambda_u}$, g is the gap and λ_u is the undulator wavelength.

This formula is only approximate since it does not take into account saturation in the ferromagnetic material. For the common case in which we approach partial saturation the field on axis (and thus K) are sensitive to the details of the geometry. For this reason we have examined a large number of numerical solutions using the computer code POISSON [3]. The undulator magnet is shown in Fig. 1. The undulator consists of two low carbon steel yokes 60 cm long, 6.4 mm high and 12 mm wide. The gap between the yokes is 4.4 mm. The yokes have square notches milled on the gap side to a depth of 1.2 mm, a width of 2.2 mm and repeating with a period of 4.4 mm. The 1.2 mm high steel 'teeth' between the notches are the pole gaps and the conductor is winded into the notches. The two yokes are clamped to two stainless steel spacing bars which define the gap to a high precision.

The space in the notches is enough for 15 turns of Nb-Ti wire. With the insulation included the wire diameter is 0.44 mm. The winding is closed over the top (bottom) of the upper (lower) yoke, so that each notch hold the inner half of one winding. The direction of the winding is reversed from one notch to the next to result in the required undulator field.

The current rating of this wire is 200 amperes. Thus the design provides 3000 ampere-turns per winding and operation at 2000 to 2500 ampere-turns is well within the wire's limit.

The result of a POISSON run for our design is shown in Fig. 2. The current of 2000 ampere-turns generates a peak field on axis of 4.5×10^3 gauss. This results in the K of 0.34 mentioned above. At 2500 ampere-turns we get a field of 5.4×10^3 gauss and K=0.4. If we use the approximate expression given above for K we get K=0.7 for NI=2000.

To estimate the manufacturing tolerances of this undulator we use Kincaid's results [4] for a compensated beam:

$$\frac{\sigma_x}{a} = 2.57\sigma N^{1.5} \tag{2}$$

where σ_x is the maximum walk of the beam, $a = \frac{K\lambda_u}{2\pi\gamma}$ is the undulation amplitude and σ is the fractional pole field error. For our conditions we find that one percent pole field error will result in a maximum beam walk of 80 μm.

The effect of undulator pole errors on the gain are given by dimensionless parameter q

$$q = \sigma^2 N^2 \frac{\frac{1}{2}K^2}{1 + \frac{1}{2}K^2} \tag{3}$$

For our case, with a $\sigma = 0.01$ we get $q = 0.023$. This value of q results in essentially no reduction in the gain.

OPTICAL RESONATOR

The optical resonator system consists of: (1) a high power resonator element, (2) precision vacuum compatible mounts with remote alignment control, (3) a He-Ne laser alignment system and (4) a pulsed Nd:YAG laser system for precise cavity length control. The resonator, its control and associated optical lines are being designed and built by Rocketdyne a Division of Rockwell International as part of the BNL-Rocketdyne collaboration.

The optical cavity is a standing wave, stable resonator consisting of a totally reflecting (> 99.9%) and a partially transmitting element; the latter serves as the outcoupling element. Its inner and outer radii of curvature are chosen such that the wavefront curvature of the FEL is unaltered in its passage through this element. This choice also facilitates injection of the alignment laser; by matching its wavefront curvature to the cavity Rayleigh length efficient coupling is assured without significant losses at the system apertures. In particular, at the 4 mm diameter wiggler bore.

Rocketdyne's three dimensional physical optics code for the FEL resonator simulations FELOPT [5] was used to design and evaluate the performance of the optical resonator. Two sets of mirror curvatures were chosen corresponding to the optimum Rayleigh length, with and without wiggler hardware as the limiting aperture [6]. A circular e-beam with zero emittance and energy spread and a parabolic radial distribution of charge was assumed. Results in Table 4 with 5% and 10% outcoupling show that the laser performance is not a strong function of the Rayleigh length and that the gain is adequate for 10% output coupling. Peak irradiance on the output element may be as high as $8\,\mathrm{GW/cm^2}$, with incident energy of approximately 100 mJ in a $1\,\mu$sec long laser pulse. In initial experiments broadband ($0.47\,\mu$m $\pm$ 10%) dielectric coated optics will be used which survived similar fluences in an earlier FEL experiment [7]. Candidate materials for substrates are *Si* for the totally reflecting element and *calcium fluoride or fused silica* for the other element. All metal optics will be considered in future experiments.

THE ELECTRON BEAM TRANSPORT SYSTEM

Two major experimental areas will be served by the ATF linear accelerator. The first area, designed for low intensity beam only will have as its focus laser acceleration of electrons by means of microlinac structures, inverse Cherenkov acceleration and related experiments; the second area will permit the exploration of shorter wavelengths FEL's and the testing of an inverse free-electron laser (IFEL) accelerator demonstration module.

The electron beam transport makes use of a short common transport line downstream of the ATF with the possibility of transverse emittance magnitude control by means of a single or a multiplicity of collimators; downstream of this an achromatic translation system permits transport of the beam to either the FEL setup or to the location of the IFEL demonstration module. At the interaction region of the FEL, the dispersion free beam can readily be controlled in terms of transverse optical parameters. Because of the relative location of the 12.5° degree dipoles and mirrors for the FEL optical cavity at least six free quadrupole parameters are required to obtain the desired beam parameters at the center of the FEL cavity. Typical local Twiss parameters are $\beta_x^* = \beta_y^* = 0.2\,\mathrm{m}$, $\alpha_x = \alpha_y = 0$, $\eta = \eta' = 0$ leading to local beam σ values given by $\sigma_x = \sigma_y = 0.125\,\mathrm{mm}$. Variation in the region of $0.1 < \beta_{x,y}^* < 1\,\mathrm{m}$ can readily be achieved for optimum overlap adjustments of laser and electron beams.

The vertical focusing of a linear undulator has also been taken into account; it acts like a focussing distributed quadrupole magnet of length $N\lambda_u$, which, for weak perturbations, as is the case here, may be approximated [8] by means of a thin lens with strength $\delta_q =$

$0.9\frac{\theta^2}{L_u}\mathrm{m}^{-1}$, where $\theta = \frac{L_u}{\rho_{eff}}$, $\rho_{eff} = \frac{\rho_u}{\eta}$ and $\eta^2 = \frac{\int_0^{\lambda_u} B\,ds}{B_{max}\lambda_u}$ with ρ_u the radius of curvature of the trajectory. For a sinusoidal field distribution undulator $\eta = \sqrt{\frac{2}{\pi}}$, hence $\rho_{eff} = \frac{1}{2}\pi\rho_u$.

One may also define the undulator β^* function for the weak perturbation case, by $\beta_u^* = \frac{L}{\sqrt{10}}\left(1 + \frac{\theta^2}{15}\right)$. If the external imposed β_{oV}^* magnitude equals β_u^* no further optical correction is required and $\beta_{oV}^* = \beta_u^*$. Alternatively, for $\beta_{oV}^* \neq \beta_u^*$, optical transport corrections have to be used and these corrections must be computed with the undulator δ_q perturbation in place. This has been done for the various cases considered here. The relevant parameters for the FEL case are: $\lambda_u = 0.88\,\mathrm{cm}$, $B_{max} = 5\,\mathrm{kG}$, $L_u = 0.6\,\mathrm{m}$, $\rho_u = 0.3365\,\mathrm{m}$, $\beta_u^* = 0.21\,\mathrm{m}, \delta_q = 3.1\,\mathrm{m}^{-1}$.

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Figure Captions

Figure 1: a) Schematic of the microundulator; b) Photograph of a two period wound model

Figure 2: Poisson calculated magnetic equipotentials

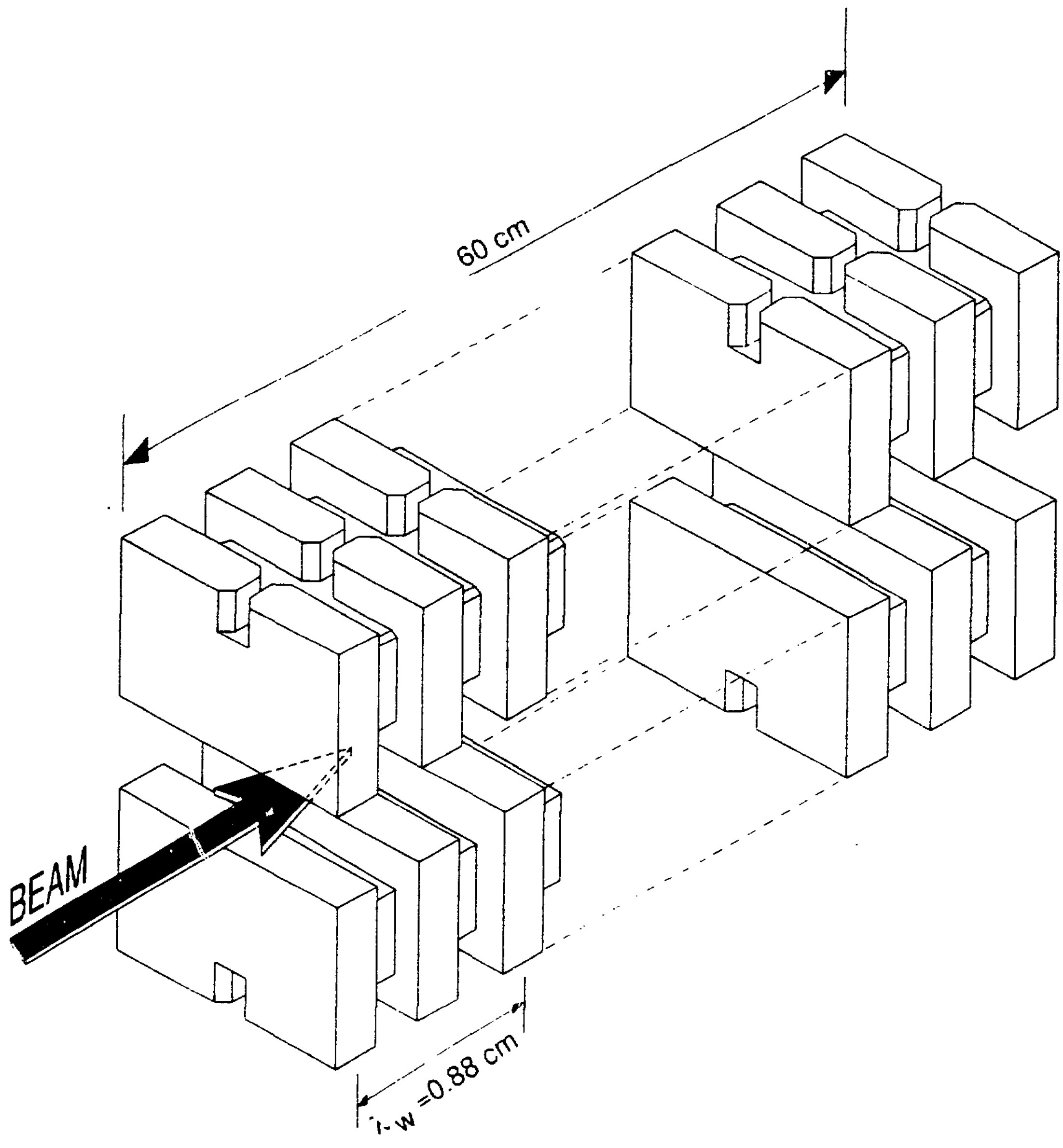
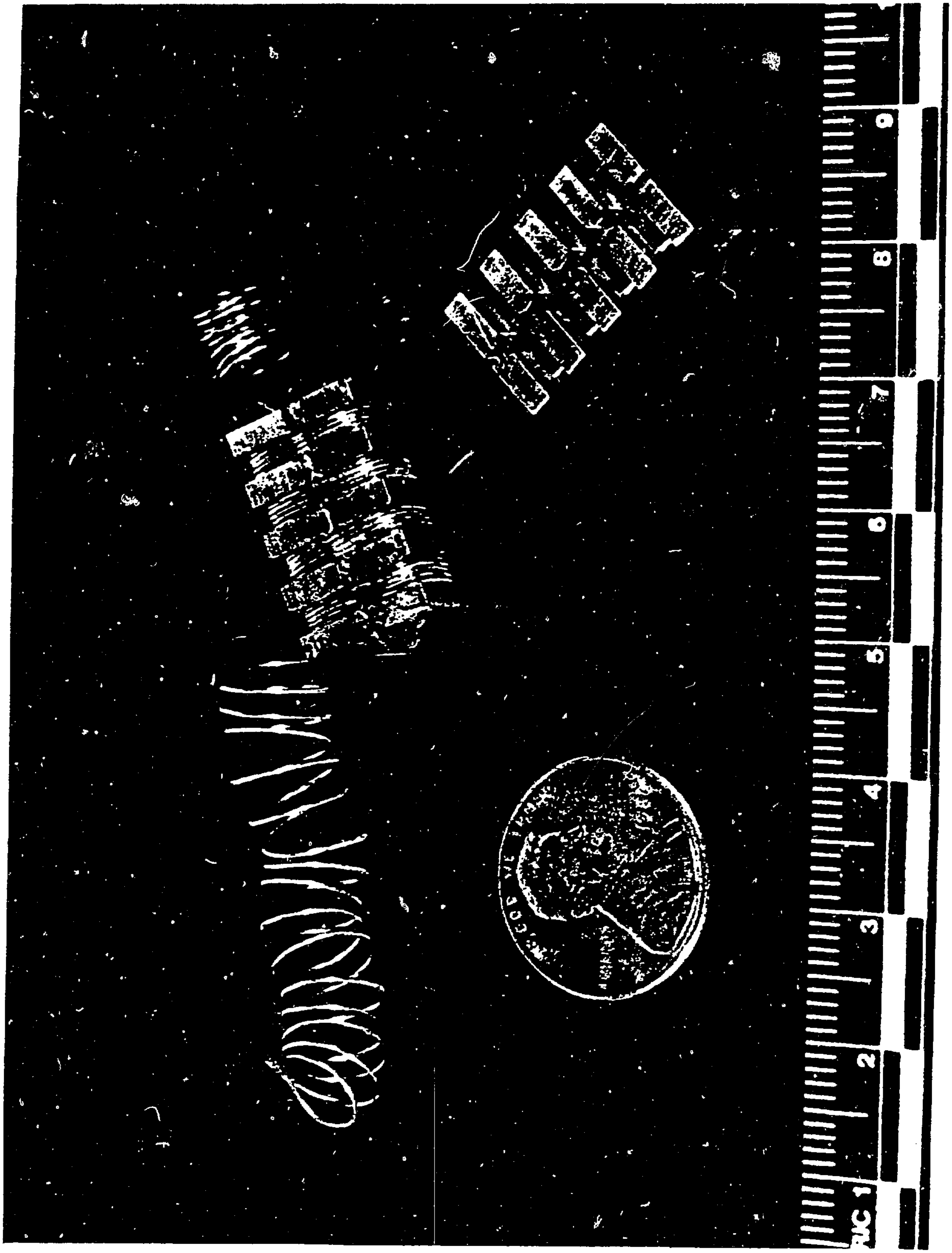


Fig (1.2)



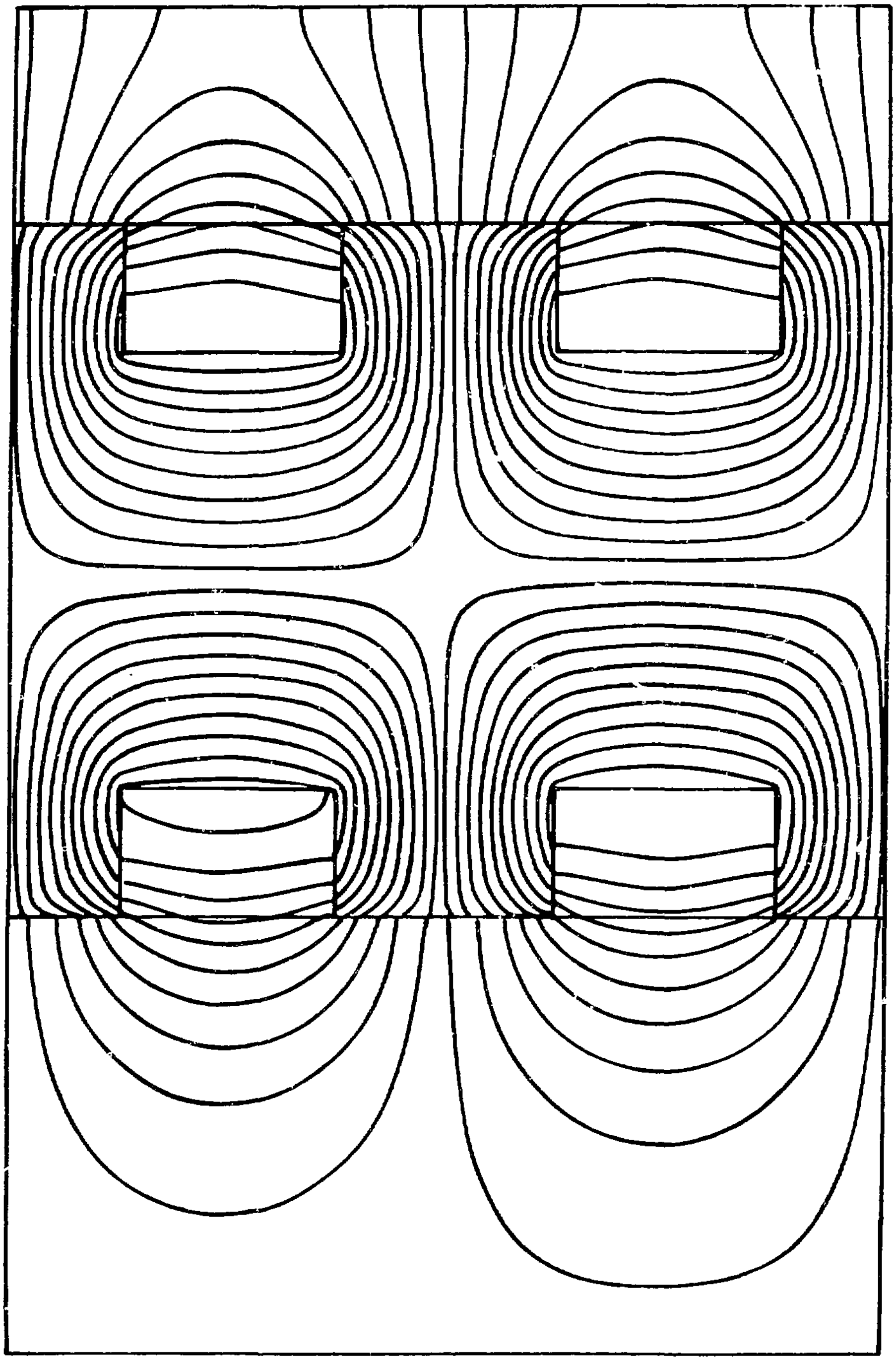


Fig. 2

Table 1: Electron beam parameters used in the simulation

Electron Beam	
Energy, γ	100
Peak current [A]	50
Bunches/macropulse	100
Effective macropulse duration [μsec]	1.25
Macropulse repetition rate [Hz]	6
Energy spread σ_E [%]	0.1
Normalized emittance ϵ_N[m − rad]	6×10^{-6}
Radius r_e [cm]	0.03
Pulse length τ_e [ps]	6

Table 4: Simulation results of FELOPT

	$Z_R = 18.53$ cm		$Z_R = 30$ cm	
	Outcoupling[%]		Outcoupling[%]	
	5	10	5	10
Intracavity Power [10^6 watt]	216.5	115.0	206.5	127.5
gain [%]	5.62	11.6	6.9	11.9
Intensity at mirror [Gwatt/cm^2]	5.15	2.64	7.86	4.65

Undulator	
Period λ_0 [cm]	0.88
Length $L = N\lambda_0$ [cm]	60
Wiggler parameter $K = \frac{eB_0\lambda_0}{mc^2 2\pi}$	0.35
Peak Magnetic field B_0 [Kgauss]	4.7
Betatron oscillation $k_b = \frac{K k_u}{\gamma\sqrt{2}}$ cm^{-1}	0.02

Table 2: Superferric undulator parameters used in the simulation

Table 3: Optical resonator design parameters

Optical Resonator	
Laser wavelength $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2\right)$ [nm]	470
Resonator length L_R [cm]	367.65
Mirror radius of curvature R [cm]	187.75