

# Free electron maser experiment with a prebunched beam

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## Abstract

An experimental project aimed at demonstrating Free Electron Maser (FEM) operation with prebunching is under way at Tel-Aviv university. The FEM utilizes a 1.0 A prebunched electron beam obtained from a microwave tube. The electron beam is bunched at 4.87 GHz and is subsequently accelerated to 70 keV. The bunched beam is injected into a planar wiggler  $(B_w = 300 \text{ G}, \lambda_w = 4.4 \text{ cm})$  constructed in a Halbach configuration with 17 periods. The wiggler utilizes a new scheme for horizontal focusing based on the use of two long permanent magnets at the sides of the wiggler. We plan to study FEM gain enhancement and radiation features due to the prebunched (superradiant) mode of operation. In an oscillator configuration the experiment should be enable study of seed injection by prebunching. Simulation of FEL operation shows an expected gain of approximately 100% and an rf output power of 5 kW. In this paper we review the design of the main parts of the experimental set-up, and present recent analytical, numerical, and experimental results.

# 1. Introduction

The emission of coherent radiation from a FEL can be enhanced if the e-beam is prebunched prior to entrance into the interaction region [1-4]. Such a scheme should allow for operation at high harmonic frequencies for high harmonics components of the beam current [3-11]. A linear theory for this scheme operated in the superradiant and stimulated superradiant mode was presented in Ref. [1] for both the low and the high gain regimes. A table top low-energy and high-current Free Electron Maser (FEM) is under development in Tel-Aviv university for experimental study of prebunched FEM physics. The basic scheme is shown in Fig. 1.

In the present scheme the electron beam is prebunched by a microwave tube operated at 10 kV, 1.0 A and driven at 4.87 GHz to produce a bunched e-beam. Upon exit from the prebuncher, the beam is accelerated to 70 keV. After a short acceleration region, the e-beam drifts, is focused and is injected into the wiggler. Tables 1, 2, and 3 contain the main FEM characteristics.

The FEM device will be operated as an amplifier in the low-gain, space-charge dominated regime. We plan to study the FEM gain enhancement and radiation features in the prebunched (superradiant) mode of operation of the single-pass FEL with a long electron pulse. If one closes the rf out-rf in loop (Fig. 1) the device becomes an oscillator. The oscillator configuration will be used to study seed injection by e-beam prebunching and amplified superradiant oscillation [1].

In this paper we describe the design of the main parts of the experimental set-up and present recent analytical, numerical, and experimental results including a novel scheme for lateral focusing in the wiggler as described in Section 2.

# 2. Wiggler field design

The planar wiggler consists of a stack of Sm-Co permanent magnets comprising 17 periods, in a Halbach arrangement. The wiggler parameters are presented in Table 2.

To attain e-beam focusing in the lateral dimension of the planar wiggler a novel scheme was developed based on two longitudinal magnets, which provide a lateral field gradient on the axis of the wiggler. To attain a circular beam  $(k_{\beta x} = k_{\beta y})$ , equal focusing strength is required in the vertical and horizontal dimensions. The horizontal gradient of the vertical magnetic field required to satisfy this condition is given by the following expression [12]:

$$\alpha = \frac{e}{2mc} \frac{B_w^2}{\gamma \beta_z},\tag{1}$$

where  $B_{w}$  is the peak value of the vertical component of the wiggler field. For the present experiment  $\alpha \equiv \partial B_{w} / \partial x$ 

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Fig. 1. The basic scheme of the prebunched beam experiment at TAU.

= 0.49 G/mm. The wiggler also includes matching magnet sections at the wiggler entrance and the wiggler exit. The magnetic field of the wiggler in three dimensions was calculated numerically using Biot-Savart's law, following Ref. [14].

For the magnets we use, the distance between the longitudinal magnets is determined theoretically [12]: D = 10.42 cm. The same result is obtained by solving the 3D

problem numerically and measuring the beam parameters experimentally. The electron beam cross-section measurement for various cases of horizontal focusing inside the wiggler are presented in Fig. 2. Good agreement is found between experimental results, theoretical calculation and numerical simulations. We used the pulsed-wire technique [13] to construct and measure the proper wiggler field and to minimize random field errors.



Fig. 2. Measurements of e-beam cross section inside the wiggler. (a) e-beam cross-section with horizontal overfocusing, (b) without horizontal focusing, (c) with horizontal focusing. (d) The current density of the e-beam inside the wiggler.

Table 1 Electron beem peremeters

Electron beam parameters	
Electron beam energy	$E_{\rm k} = 70 {\rm ~keV}$
Beam current	$I_{0} = 1.0 \text{ A}$
Beam diameter	$r_{\rm b} = 2.0  {\rm mm}$
Plasma frequency	$f_{\rm p} = 0.5  \mathrm{GHz}$
Macropulse duration	$\dot{\tau} = 1-20 \ \mu s$
Electron bunch duration	$\tau_{\rm eb} = 0.2$ ns
Energy spread	$\sigma_{\mathscr{E}} / \mathscr{E} pprox 0.5\%$

Table 2

Planar wiggler parameters

$B_{\rm w} = 300  {\rm G}  (a_{\rm w} = 0.12)$
$\lambda_{\rm w} = 4.4 \ {\rm cm}$
$N_{\rm w} = 17$
$L_{\rm w} = 0.748 {\rm m}$
g = 5.1  cm
$k_{\beta x} = k_{\beta y} = 23.4 \text{ rad/m}$

#### 3. Microwave interaction region

The parameters of the waveguide operating in the  $TE_{10}$  mode which has been chosen for FEL interaction are given

Table 3 Microwave (TE<sub>10</sub> mode) parameters

Waveguide dimensions	$a \times b = 47.55 \times 22.15 \text{ mm}^2$
Cutoff frequency	$f_{co} = 3.15 \text{ GHz}$
Frequency	$f_{\rm s} = 4.87 \; {\rm GHz}$
Signal wavelength	$\lambda_{\rm s} = 6.2 \ {\rm cm}$
Losses	$\alpha = 0.04 \text{ dB/m}$
Power filling factor	$A_{c} / A_{em} = 0.063$

in Table 3. The fundamental mode  $TE_{10}$  of a WR-187 rectangular waveguide (47.55 × 22.15 mm<sup>2</sup> cross section) is used for the FEM interaction. The cutoff frequency of this mode is 3.15 GHz and the system is operated in a frequency range of 4 to 6 GHz. In this frequency range, the only mode that can propagate in the waveguide is the fundamental mode (TE<sub>10</sub>), all the higher order modes are cut off. The dispersion curves are given in Fig. 3d.

The electron beam enters the interaction region through a 9 mm diameter hole in the waveguide bend. This hole is followed by a cylindrical section below cutoff so that it allows injection of the beam with no rf power loss and with rf power reflection of less than 5% of the total input power in the 4–6 GHz frequency range [15]. In order to increase the power filling factor we may insert profiles



Fig. 3. Predicted radiation emission from prebunched beam. (a) The gain vs. the signal frequency. The maximum gain is achieved at 4.87 GHz. (b) The power generated due to prebunched beam as a function of frequency. The peak power appears at 5 GHz. (c) The power generated due to stimulated prebunched beam emission as a function of frequency. The peak power appears at 5 GHz. (d) The dispersion curves and the electron beam line. The electron beam is synchronized with the fundamental mode  $TE_{10}$ . In a frequency range of 4–6 GHz, all the waveguide modes except  $TE_{10}$  are cutoff.

along the waveguide walls. This lowers the cutoff frequency and enables reduction of the waveguide dimensions for the same cutoff frequency. Consequently, the wiggler gap can be decreased and the wiggler field increases resulting in higher gain.

### 4. Gain and power calculation

1

The FEL gain and radiated power were calculated for a linear model of a prebunched cold beam [1]. This model yields the following gain-dispersion equation:

$$C_{s}(s) = \left\{ \left[ \left( sL - i\bar{\theta} \right)^{2} + \bar{\theta}_{pr}^{2} \right] LC_{s}(0) + \left[ \left( sL - i\bar{\theta} \right) M_{j} e^{i\bar{\phi}_{j}} - iM_{v} e^{i\bar{\phi}_{v}} \right] \left[ \frac{P_{B}}{\mathscr{P}_{s}} \right]^{1/2} \right\} \right\} \\ \left/ \left\{ sL \left[ \left( sL - i\bar{\theta} \right)^{2} + \bar{\theta}_{pr}^{2} \right] - i\overline{Q} \right\},$$
(2)

where  $\overline{\theta}$ ,  $\mathscr{P}_s$ , and  $k_z$  are the normalized detuning parameter, the normalization power and the wavenumber of the propagating waveguide mode, respectively. The reduced plasma frequency parameter is:

$$\bar{\theta}_{\rm pr} = \frac{\omega_{\rm p}}{v_{0z}} Lr, \qquad (3)$$

where  $\omega'_p = [e^2 n_0 / (\epsilon_0 \gamma_0 \gamma_{0z}^2 m)]^{1/2}$  and r is the plasma frequency reduction factor. For our FEM design parameters r is in the range of 0.2–0.5. The bunching power parameter  $P_B$  is given by:

$$P_{\rm B} = \frac{1}{16A_{\rm em}\,\beta_{\rm ph}} \sqrt{\frac{\mu_0}{\epsilon_0}} \left[\frac{\bar{a}_{\rm w}}{\gamma_0\,\beta_{0z}}I_0L\right]^2,\tag{4}$$

where  $\beta_{\rm ph}$  is the phase velocity. The amplitude of the generated radiation due the prebunched beam is proportional to the velocity and current indices of modulation which are defined as  $M_{\rm j} e^{i\tilde{\phi}_{\rm j}} = \tilde{J}_z(0)/J_0$   $M_{\rm v} e^{i}\tilde{\phi}_{\rm v} = \tilde{V}_z(0)/v_{0z}kL$ , where  $\tilde{\phi}_{\rm j}$  and  $\tilde{\phi}_{\rm v}$  are the phases of the current density and axial velocity modulation waves with respect to the ponderomotive wave phase. The gain parameter is given by:

$$\overline{Q} = \frac{1}{4} \frac{A_{\rm e}}{A_{\rm cm}} \left[ \frac{\overline{a}_{\rm w}}{\gamma_0 \beta_{0z}} \beta_{\rm ph} \right]^2 \left[ \frac{\omega}{v_{0z}} \right]^2 L^3 k_z.$$
<sup>(5)</sup>

The field amplitude C(L) is derived by taking the inverse Laplace transform of the gain Eq. (2):  $C(L) = \mathscr{L}^{-1}\{C(s)\}$  and the output power is found from the relation  $P_{\text{out}} = |C(L)|^2 \mathscr{P}_{\text{s}}$ . The square of the absolute value (after transformation) of the two parts in Eq. (2) produce three

terms corresponding to three different radiation emission processes. The curves of gain and radiated power of the various radiation processes are shown in Figs. 3a, 3b, and 3c. The gain of a conventional FEL (without prebunching) is obtained from the first part on the r.h.s. of Eq. (2), the pure prebunched beam emission (zero input signal) is due to the second term (squared) in this equation.

The last emission process results from the mixed term which involves the input signal and the bunched beam parameters. We define the radiation due to this term as a stimulated prebunched beam emission. The curves in Figs. 3 are obtained with the FEM design parameters which are presented in Tables 1, 2, and 3, and with the assumptions that  $\bar{\phi}_v = \bar{\phi}_j = 0$ ,  $M_v = 0$  and  $M_j = 0.01$ . The device will be operated by inserting an rf signal to either or both input ports as shown in the experimental scheme (Fig. 1). We shall experimentally verify the three radiation processes described by theory and measure the corresponding emission curves (Figs. 3).

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