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For Free Electron Lasers

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ABSTRACT

We present the design, construction, and test results of a novel micro-wiggler structure with a periodicity of 2.4 mm for free-electron laser (FEL) applications. The experimentally demonstrated tunability of field amplitudes provides versatile means for field tapering, optical klystron configurations, improving field uniformity, and electron beam matching at the wiggler entrance.

INTRODUCTION

Short period (1–10 mm) wigglers for free-electron laser (FEL) applications has been a subject of considerable interest.[1-5] Besides their compactness, such systems have the advantage of producing higher frequency radiation with a given electron energy, or conversely, it reduces the electron energy required to access a given wavelength. This is illustrated in Fig. 1a where we plot the electron beam energy required as a function of the wiggler periodicity, so as to achieve radiation of a given wavelength. The single pass gain expected from micro-wiggler-driven infrared FELs operating in the small signal regime is shown in Fig. 1b.

The wigglers proposed in previous works[2-4] lack a simple but precise field tuning mechanism so important in numerous applications. In this paper, we report a novel micro-wiggler with this unique flexibility. The 30-periods micro-wiggler, with a periodicity of 2.4 mm, is shown in Fig. 2. The fabrication technique used in this prototype is an extension of that used in the multi-channel magnetic recording heads[6], and will be described in more

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detail in the next section. The wiggler consists of a periodic assembly of tiny electromagnets each of which is energized by its own current windings. The magnetic field in each half-period is independently controllable and the experimentally demonstrated tunability provides versatile means for achieving the wiggler field required for optimal FEL operation, such as reduction of random field errors; field tapering; optical klystron configurations; and electron beam matching at the wiggler entrance. The measured operating characteristics of the micro-wiggler in the linear regime, (that is, well below saturation of the magnet material) agree very well with both analytical predictions and numerical models.[7] The saturation behavior in the magnet structure is also studied experimentally and by nonlinear finite element simulations.

EXPERIMENT

As shown in figure 2, the micro-wiggler is assembled in two aluminum half brackets, each with 60 precision-cut slots, held together with epoxy and bolts. The magnet elements are thin AlFeSi cores wound with 160 turns of 40 gauge wire, One of these C-shaped elements is shown in Fig. 2b together with the computed field lines. These cores are loaded into the slots in the half-brackets and potted. Terminal boards (electrical interfaces) are connected to the core windings and inserted into the half-brackets. The whole assembly is then lapped and gapped to form the 3 mm air gap (beam channel). All mechanical tolerances are held within 10 μm such that an undulator period error of less than 0.3% is achieved. The error due to machining is controlled in a non-cumulative fashion to help sustain the phase synchronism in the FEL interaction. The parameters of our micro-wiggler (designated MW-1) are listed in the first column of Table 1.

In all the measurements, the micro-wiggler is driven by one single power source with all the electromagnet channels being excited in parallel. The magnetic field in each half-period is independently controlled by varying the current using a series potentiometer. Both DC and 60 Hz AC power supplies are used in low field CW tests. The results show very little

AC effects (e.g. eddy current loss) and there is no substantial difference in the AC and DC field measurements. For high field tests, a special pulser circuit was constructed. Upon triggering, the low level electronics in the circuit fire the high power SCRs and switch a clean half-period sine wave from the 60 Hz power line into the micro-wiggler. The rise time and pulse width of the 8 ms pulse is much longer than the 0.5 ms rise time of the magnet elements. The magnetic field measurements are made with a miniature Hall probe mounted on a motorized translation stage. The diameter of the probe is 0.24 mm and corresponds to an active area of 0.045 mm^2. The experiment was conducted at room temperature with no active cooling in the magnet structure.

In the linear operating regime of the magnet, (namely well below saturation of the magnet material) we obtain a calibration factor of 110 Gauss/Amp on axis, in good agreement with calculations[7].

The tunability of the field amplitudes is demonstrated as follows: with equal settings on the tuning potentiometers, the measured field shows a 15% variation in peak field amplitudes as shown in figure 3a. The distinct field spikes at the entrance and the exit are present as expected and are due to the abrupt termination of the current windings. Fig. 3a also illustrates the effect on the field amplitudes when one of the channels is not energized. After carefully tuning the circuit (Fig. 3b), the peak field variations can be kept well below 1%, and the wiggler entrance field can be fully adjusted to fit the optimal beam injection condition. These adjustments are possible as a result of the coupling of magnetic fields from neighboring magnets.

The thickness t (as measured in the axial direction) of the magnet yoke is important in determining the amplitude of the higher spatial harmonics. When t is too small, higher harmonics become significant.[7] With a core thickness t of $l_\omega/4$, the partial cancellation between channels generates a nearly perfect sinusoidal field pattern (Fig 3b). The third harmonic on axis is measured to be less than 0.5%, a result which likewise agrees with computations[7].

The measured transverse field profile across the gap, $B_y(y)$, agrees well with the simulation (Fig. 4a), and closely follows the usual $cosh(k_w y)$ dependence. The field variations $B_y(x)$ along the long (x) dimension of the pole face, have also been measured and computed as shown in Fig. 4b. The slight asymmetry is due to the core geometry.

Our prototype (MW-1) wiggler has a maximum magnetic field amplitude of 600 G. This limitation is due to several factors: (a) use of magnetic material having low saturation (~ 10 kG); (b) a non-optimal core geometry (Fig. 2b) in which premature saturation occurs in the current winding arms of the yoke rather than in magnet gap region; and (c) a rather unfavorable gap width to wiggler period ratio.

Columns 2 and 3 of Table 1 illustrate the operating parameters of an improved design (MW-2) using soft transformer iron that is now under active consideration. The magnitudes given in the Table are based on detailed linear and nonlinear simulations and refer to operation when the magnetic material is nearly saturated in the vicinity of the gap. The shape and the calculated magnetic flux distribution of this new core is illustrated in Fig. 2c.

DISCUSSION

A central issue in the micro-wiggler design is the question of cooling. In short pulse operation, the temperature rise is solely determined by the thermal mass of the coils. For copper coils operating at 100 °C, the maximum current is calculated to be 6 A per channel for 8 ms pulse duration. Experimentally, the maximum current was measured under two conditions: 10 Amperes with all the channels tightly seated in the slot structure versus 50 Amperes for a single core piece excited in room temperature air. The comparison indicates the possibility of higher current operation with provisions for cooling the entire micro-wiggler stack. Precooling the copper coil magnet down to nitrogen temperature ($77°K$) increases the maximum current by a factor of 3. Further precooling is neither economical nor effective because of the temperature dependence of copper resistivity and

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heat capacity. Longer pulse ($\simeq 100$ ms) operation of micro-wigglers can be achieved by using more turns so as to achieve a larger gauss/amps ratio. For DC operation, it is imperative to use superconducting coils. For example, using 32 gauge NbSn wire and the same prototype parameters, and assuming that the permeability stays high enough at helium temperature, the critical current is estimated to be 20 A.

In conclusion, we have designed, constructed and tested a 30 period micro-wiggler prototype with a 2.4 mm wavelength. The tunability of the longitudinal field profile is demonstrated. The operating characteristics of the magnet in the linear regime agree well with both analytical and numerical calculations. With proper precooling and the use of high saturation core materials, long pulse operation at high field is realizable. Optimized designs for wiggler periods of 2.4 mm and 5 mm are given in Fig. 2c and Table 1. Construction of these wigglers is under active consideration.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Fig. 1. (a) Required accelerator energy and (b) small signal gain vs. micro-wiggler periodicity for FELs operating in infrared.

Fig. 2. (a) Photograph of the 30 periods MW-1 micro-wiggler. (b) The shape and calculated 2D flux pattern for the prototype MW-1; (c) The shape and calculated 2D flux pattern for an optimized configuration.

Fig. 3. Hall probe measurement of the wiggler field on axis under (a) untuned and (b) tuned conditions. Notice the drastic improvement of uniformity and the reduction of end spikes in (b), relative to (a).

Fig. 4. (a) Comparison of measured and calculated transverse field profile B_y as a function of y, and (b) comparison of measured and calculated transverse field profile B_y as a function of x (Fig. 2b explains the coordinate system).

Table 1. Parameters for the experimentally tested micro-wiggler MW–1, and optimal conceptual design for MW–2.

	MW–1	MW–2	
Wiggler periodicity ℓ_w (mm)	2·4	2·4	5
No. of periods	30	30	50
Core material	AℓFeSi	FeSi	FeSi
Material saturation (kG)	10	19.7	19.7
Gap width (mm)	3	3	2·4
Core thickness t (mm)	0.6	0.6	1
No. of windings	160	800	800
Max. wiggler amplitude on axis (kG)	0.6	1·3	3·2
Current at maximum field (A)	10	2·5	2·5

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(a)

(b)

Current : 40A
Beam Diameter : 0.4mm
Number of Periods : 80
Peak Field : 4kG
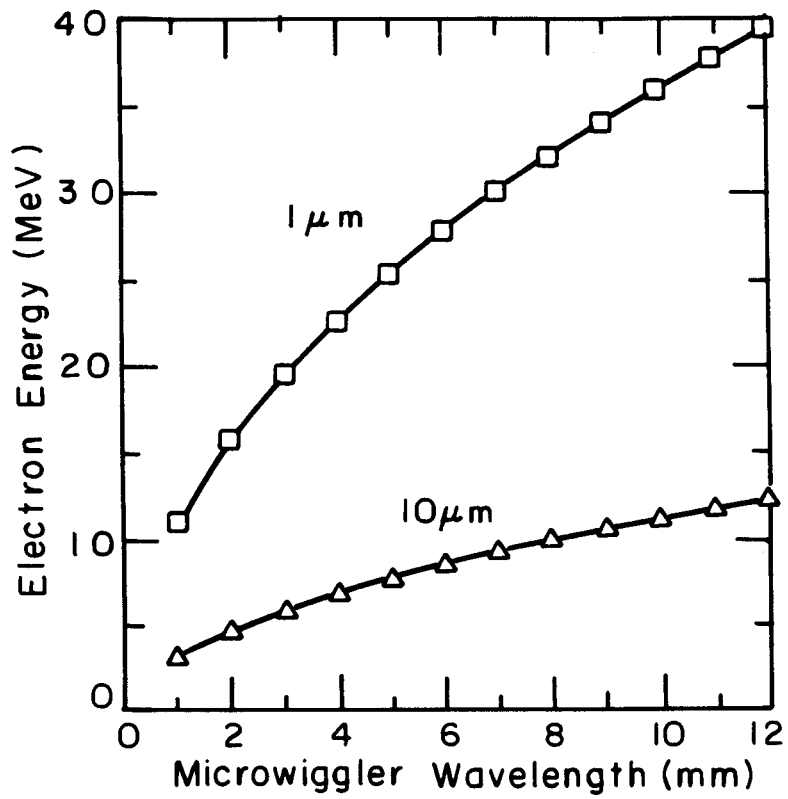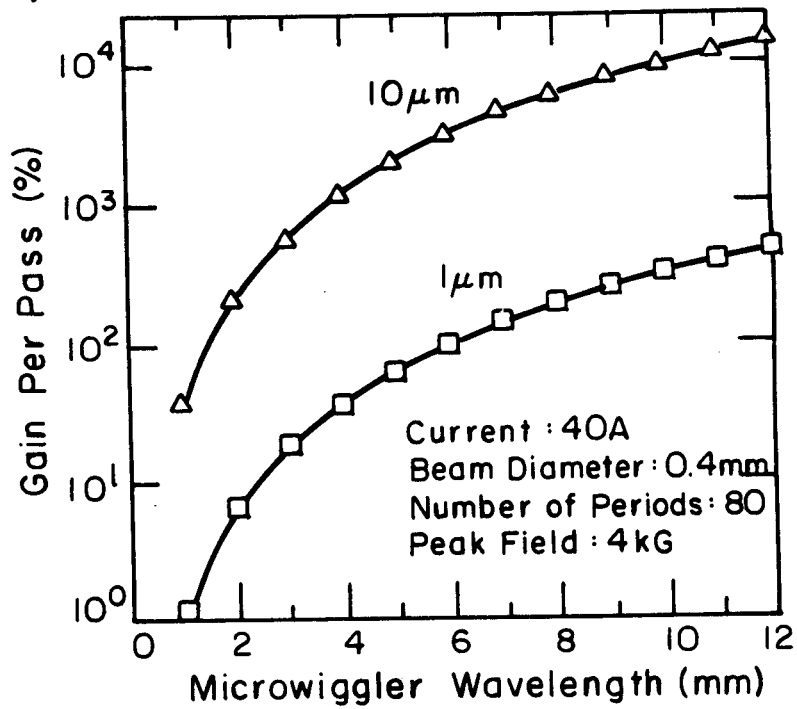
Fig.1.Chen,Bekefi,DiCecca
Temkin

(a)

(b) |— 3mm —|

(c)

|— 10 mm —|

Fig.2 Chen,Bekefi,DiCecca,
Temkin

(a) Untuned

± 110 Gauss / Amp

one channel left off

(b) Tuned

± 100 Gauss / Amp
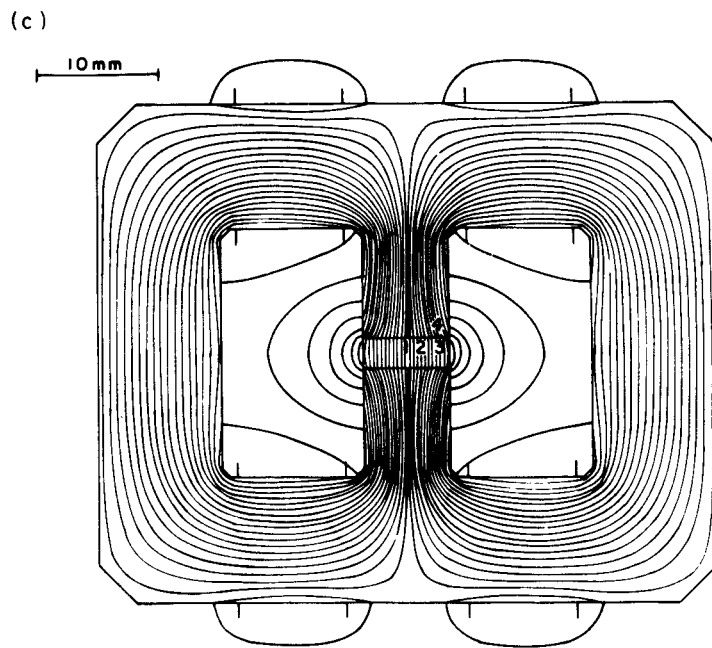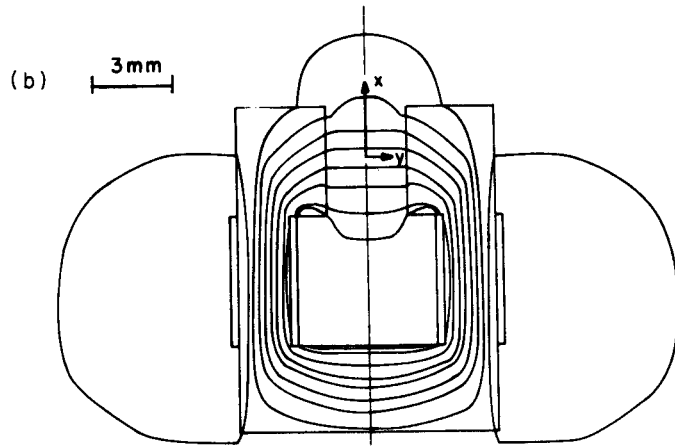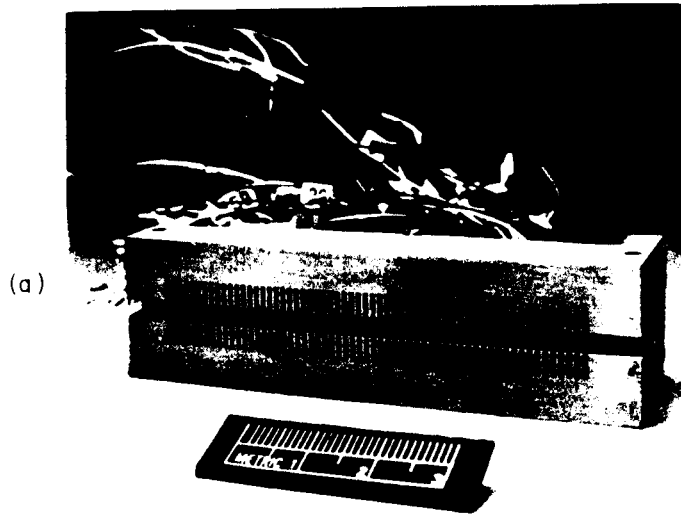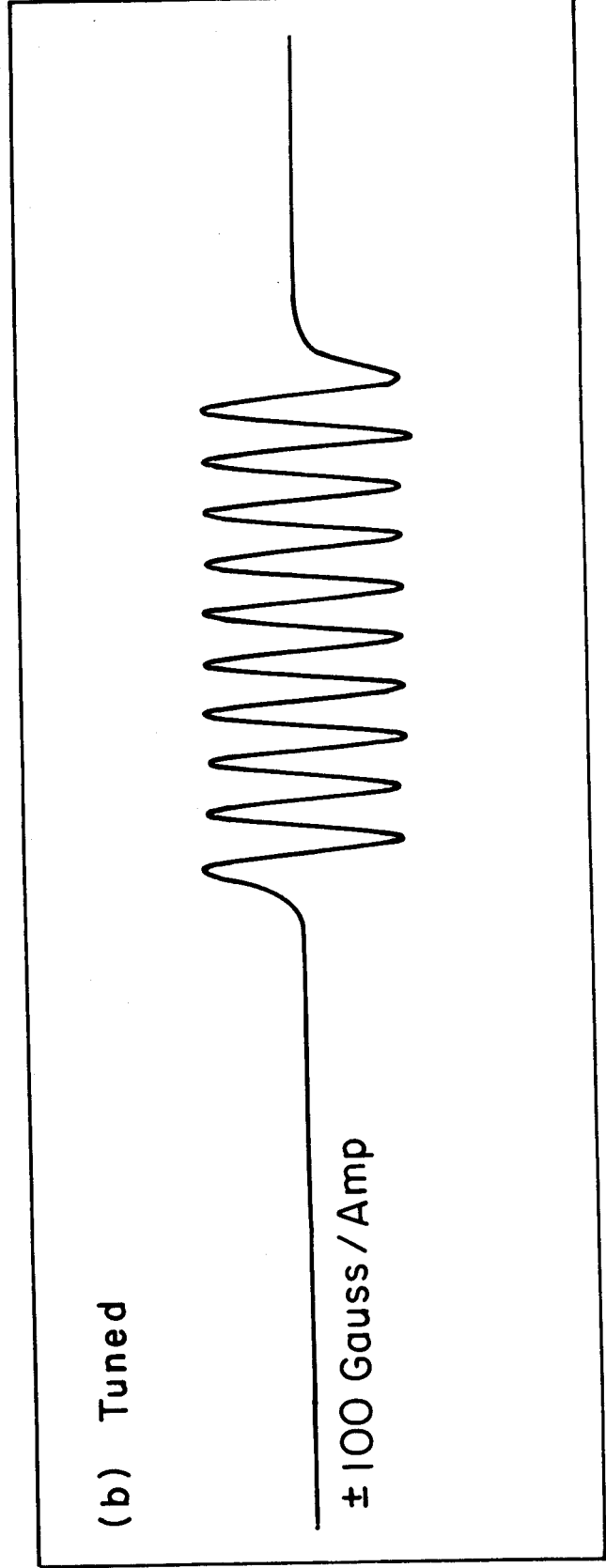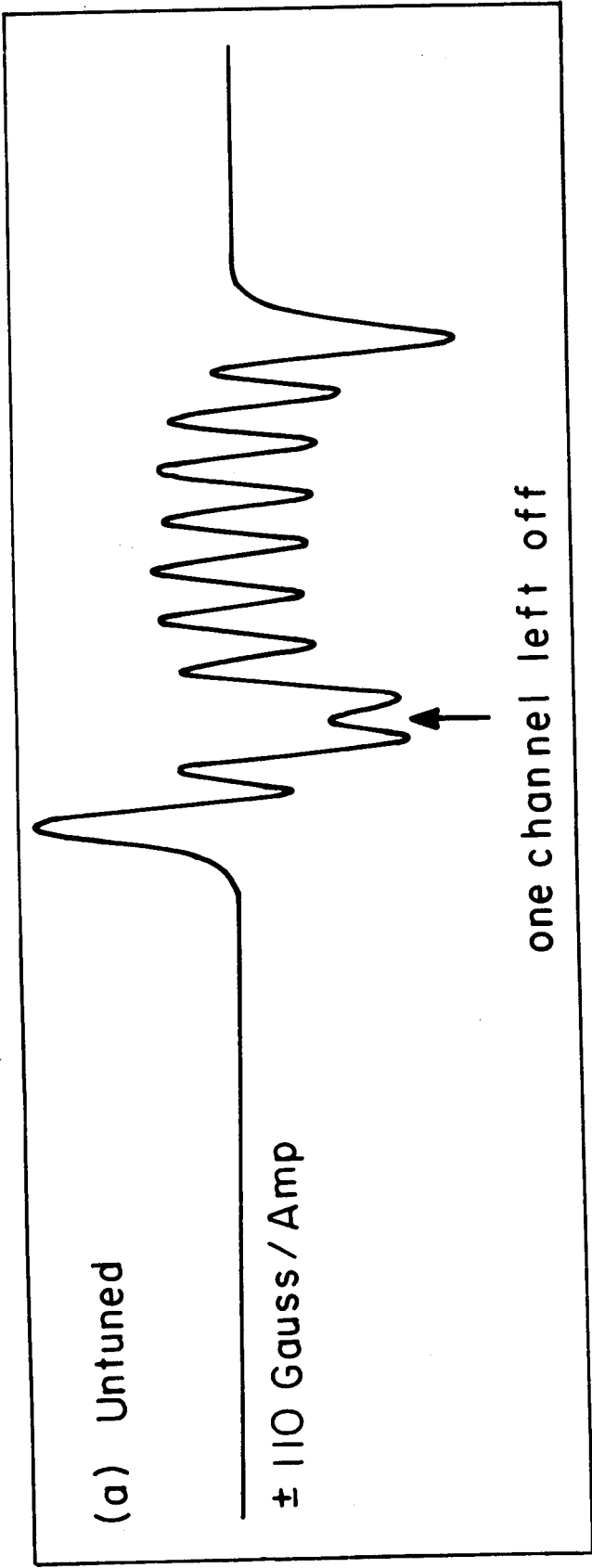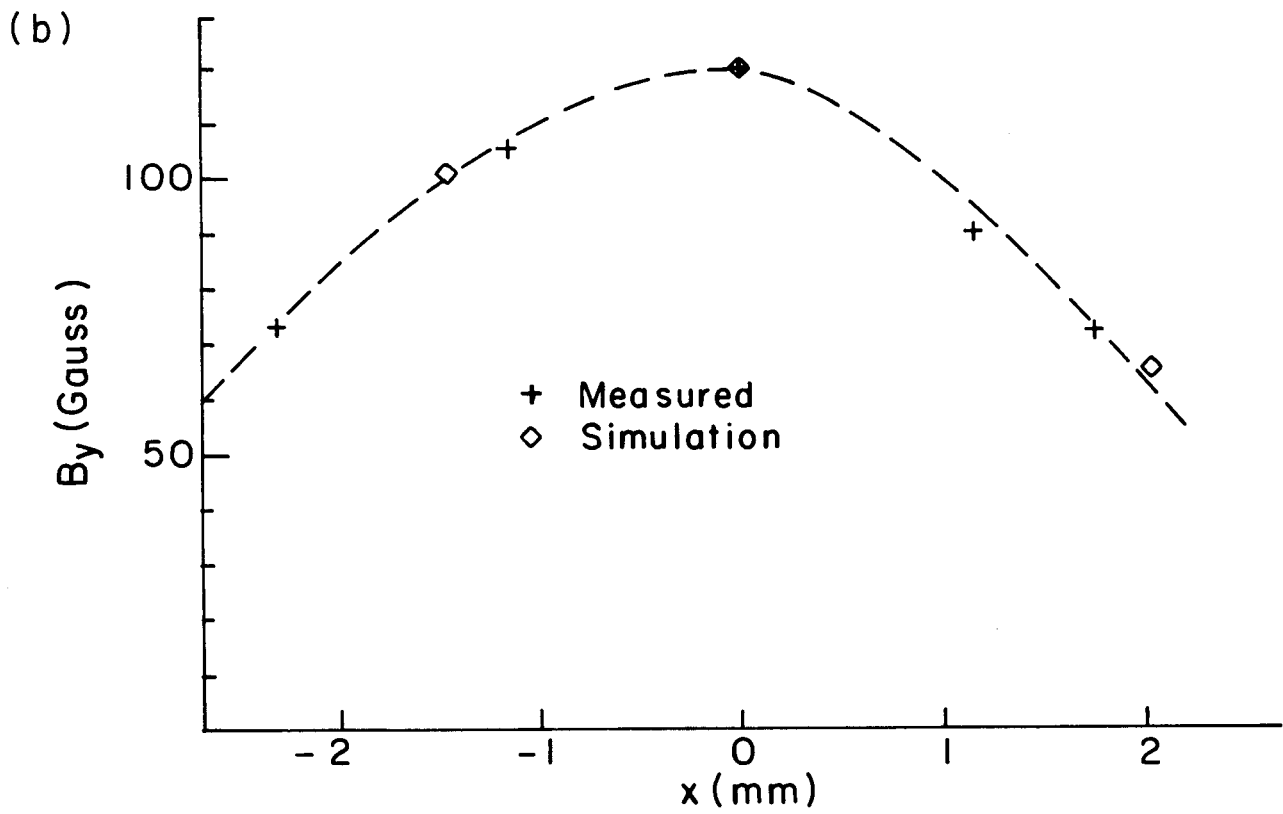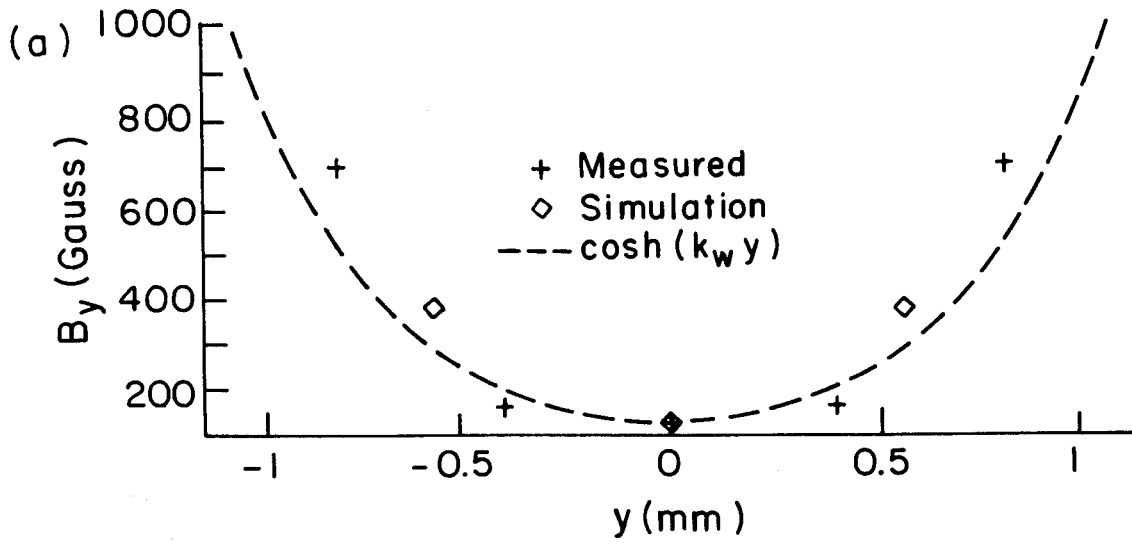
Fig.3. Chen,Bekefi,DiCecca,
Temkin

(a)

(b)

Fig.4 Chen,Bekefi,DiCecca
Temkin