

A 2 TESLA FULL SCALE HIGH PERFORMANCE PERIODIC PERMANENT MAGNET MODEL FOR ATTRACTIVE (228KN) AND REPULSIVE MAGLEV

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Two 214.5 cm. long high performance periodic (26 cm period) permanent magnet half-assemblies were designed and constructed for use as a wiggler using Nd-B-Fe and vanadium permendur as hard and soft magnetic materials by Field Effects, a division of Intermagnetics General Corporation. Placing these assemblies in a supporting structure with a 2.1 cm pole to pole separation resulted in a periodic field with a maximum value of 2.04 T. This is believed to be the highest field ever achieved by this type of device.

The attractive force between the two 602 kg magnet assemblies is 228 kN, providing enough force for suspension of a 45,500 kg vehicle. If used in an attractive maglev system with an appropriate flat iron rail, one assembly will generate the same force with a gap of 1.05 cm leading to a lift to weight ratio of 38.6, not including the vehicle attachment structure. This permanent magnet compares well with superconducting systems which have lift to weight ratios in the range of 5 to 10.

This paper describes the magnet assemblies and their measured magnetic performance. The measured magnetic field and resulting attractive magnetic force have a negative spring characteristic. Appropriate control coils are necessary to provide stable operation. The estimated performance of the assemblies in a stable repulsive mode, with eddy currents in a conducting guideway, is also discussed.

The development of this concept and overall configuration was internally funded by Intermagnetics. The design and construction of the permanent magnet assemblies was performed under a U.S. Department of Energy subcontract from the Stanford Synchrotron Radiation Laboratory (Stanford University Contract No. 7144.)

INTRODUCTION

Commercial development of magnetic suspension and propulsion systems in Japan¹ and Europe² have utilized resistive coils in the vehicle as part of a magnetic circuit that

includes the guideway. These systems have a relatively small gap of the order of 1 cm or less. The limitation on resistive coils is generally the power dissipated in the coils.

Superconducting coils, with no resistive losses, have been selected for the new high speed Yamanashi test line now under construction in Japan³. These coils will operate at a gap of 11 cm. The only resistive losses in superconducting systems are in the guideway. In general, the magnetic suspension has little damping by itself and power must be supplied to achieve acceptable dynamics.

Permanent magnets may be used to supply the steady component of force thereby reducing resistive coil system power levels. Power to correct for negative spring constants in attractive systems as well as other dynamic requirements will still be required.

The permanent magnet wiggler periodic arrays built and described in this paper have large force capability and can be tailored in length by adding or subtracting poles. They can also be placed in multiple parallel arrays to achieve varying width. Thus, the design provides flexibility which may be utilized for maglev applications. The significant features of the magnetic arrays are discussed in this paper, followed by a review of their potential for use as maglev system elements.

WIGGLER MAGNET PROGRAM SUMMARY

A unique 2.04 T hybrid wiggler was designed and fabricated for Beamline 9 of the Stanford Synchrotron Radiation Laboratory (SSRL) by Field Effects, a division of Intermagnetics General Corporation⁴. The wiggler, a periodic array composed of permanent magnets and magnetic poles, provides a high strength alternating magnetic field that bends an electron beam to generate synchrotron radiation. The 16 milliradian fan of high energy x-rays produced is utilized for research in structural molecular biology and other scientific disciplines. The basic SSRL performance specifications⁵ include a magnetic field at minimum gap of at least 1.9 T. The 2.04 T achieved exceeded this specification.

The magnetic structure makes use of Neodymium-Iron-Boron (Nd-Fe-B) permanent magnet materials and vanadium permendur for the pole pieces in a compact pole design. This configuration uses considerably less magnet pole material than conventional hybrid or wedge pole designs^{6,7,8}.

The large magnetic forces at minimum gap, and the need to operate reproducibly at lower magnetic fields and lower forces with larger gaps, required an overall mechanical design that was suitably rigid with provisions for accurate, reproducible gap adjustment. While this system was built for other purposes, it is a full-scale permanent magnet model

of a type which may be used for magnetic levitation. That is, its measured performance can be used as a basis for permanent magnet suspensions for other applications.

Wiggler Configuration And Operation

A schematic of the overall configuration of the wiggler is contained in Figure 1. Dimensions and weights are given in Table I. Figure 2 shows a photo of the completed assembly. The Wiggler consists of upper and lower permanent magnet arrays mounted on backing beams. The backing beams are connected by cross beams to four precision rotating ball screws which provide symmetrical parallel vertical motion to the upper and lower moveable assemblies (magnets, backing beams and cross beams).

The large magnetic forces at minimum gap are transmitted through the four rotating ball screws which are chain driven by a single stepper motor through gear reducers. This includes a brake assembly to prevent unplanned motion. The gap position is determined by an encoder mounted on one of the ball screws which is calibrated over the full range of gaps using laser measurement techniques.

The overall assembly is designed to provide the large magnetic forces at minimum gap (over 228 kN) with minimal deflections, support gravity and seismic loads, and allow accurate installation of the wiggler onto the electron beam.

A remotely-controllable drive system opens and closes the wiggler. The drive system consists of a motor, gearbox and brake, and is capable of continuous or intermittent scanning using a computer control. The drive system is capable of movement through the full gap range of 2.1 to 21 cm in 55 seconds.

A laser interferometer system was used to initially measure and calibrate gap as a function of encoder count. This system has a resolution of 10 nanometers. The gap is varied from approximately maximum to minimum in 20 encoder count steps. This establishes the calibration and reproducibility of position versus encoder count. The repeatability error over the full range of gaps was determined to be $\pm 24 \mu\text{m}$ and $\pm 31 \mu\text{m}$ in two sets of measurements. Most of this variation is due to a load reversal at one location. If this is neglected, the repeatability is $\pm 15 \mu\text{m}$.

Wiggler Magnetic Characteristics

The wiggler consists of an upper and lower array of 15 physically identical full strength pole assemblies each. Each pole assembly is one half of a period length. There are half strength integrated field lower strength poles to provide appropriate transitions along the beam path at both ends.

For each of the arrays, the pole assemblies are arranged in alternating polarity on a stainless steel backing beam to support the large magnetic forces, as shown in Figure 3. The polarity of the upper and lower magnetic pole arrays are such that their magnetic fields add. The upper and lower pole face arrays must be parallel and precisely positioned in the directions parallel and perpendicular to the beam.

The pole design and assembly process allows measurement and mechanical adjustment of individual poles prior to assembly. Further magnetic measurement and adjustment of individual poles in the assembled array is also possible. Using this approach three adjacent poles in the end regions, one of half and two of full strength were adjusted. Figure 4a gives the values of magnetic field after correction as a function of position along the beam. Figure 4b provides the details for a single pole. These corrections resulted in a final on-axis pole to pole peak field variation at minimum gap of 0.48%. The principal magnetic parameters are listed in Table II.

The peak on-axis magnetic field is 2.04 T at the minimum gap of 2.1 cm. We believe this to be the highest reported magnetic field for a permanent magnet wiggler at this time.

Figure 5 compares predicted and measured magnetic field as a function of gap, indicating excellent agreement. The field estimates were made using 2D finite element software⁹, 3D analytical techniques, and a 1/3-scale, 1/2-period model which was fabricated to confirm field characteristics. Figure 6 illustrates the rapid increase in attractive force between the upper and lower assemblies as the gap decreases and clearly demonstrates the negative spring characteristic. This figure utilizes calculated force which was subsequently confirmed by measured magnetic field versus gap data. Figure 6 can be converted to a lift-to-weight ratio by dividing by the appropriate magnetic structure weights.

Maglev Magnet Analysis

Although the previously described wiggler system was not intended for attractive or repulsive suspension, the adjustable gap feature allows magnetic field and magnetic force

to be varied. The as-built system is configured in an attractive mode, where the polarity of the upper poles are opposite those of the facing lower pole pieces and both add to the magnetic field in the central gap as illustrated in Figure 3.

A repulsive force could be achieved with the wiggler by shifting the assembled arrays horizontally one half period so that the polarity in the pole pieces on both sides of the gap is the same. Alternately, the polarity of one array can be switched mechanically, again resulting in like polarity poles aligned to each other across the gap, as indicated in Figure 7.

For the purposes of maglev analysis, the wiggler minimum achievable gap (2.1 cm) and magnet structure assembly weight (602 kg) is utilized for levitation calculations. This represents maximum lift to weight performance. Wiggler field measurements were made in the attractive mode configuration using Intermagnetics' - built computer-positioned Hall probes or coils. Repulsive mode performance was computed using 2D finite element magnetic field calculations.

- Magnetic fields were determined for various gaps, using two boundary conditions:
1. Magnetic field perpendicular to the central plane - attractive condition.
 2. Magnet field parallel to the axis on the central plane - repulsive condition.

Physically, the first boundary condition represent either a single array with a magnetic guideway, Figure 8, or two permanent magnet arrays in a attractive mode at twice the pole to magnetic guideway gap, Figure 3. The magnetic field estimates for the magnetic guideway case would be valid at any practical speed provided the guideway was appropriately designed to minimize eddy currents. Permanent magnets in the guideway generally would not work well at other than zero speed because of the periodic character of the arrays. The exception to this is when the periodic array is placed transverse to the direction of motion.

The second boundary condition represents either a single array operating above a highly conducting guideway, Figure 9, or two opposing permanent magnet arrays, Figure 7, at twice the pole to guideway distance. Because the repelling eddy currents move with the array, it represents a practical maglev configuration. As in the attractive case, with permanent magnets in the guideway, the guideway magnets must be placed transverse to the direction of motion because of the periodicity of the array.

It is possible to design a nonperiodic array (in the direction of motion) to operate in either attractive or repulsive modes by using an appropriate non-periodic permanent magnet guideway.

Table III summarizes the maximum performance at minimum gap conditions for each of the operating conditions of the two permanent magnet arrays discussed above. Maximum performance as previously discussed corresponds to minimum gap between the two arrays. Alternatively, it assumes infinite permeability or conductivity, as appropriate for the guideway.

The two attractive conditions indicated in Table III result in lift-to-weight ratios approaching 40 in both cases. The table clearly points to the fact that an "energized" permanent magnet guideway in an attractive mode has twice the operating gap of the "passive" magnetic guideway. We can also conclude that for equal gaps, permanent magnets in the guideway will result in about twice the lift-to-weight ratio.

The two repulsive modes each have a lift-to-weight ratio of just below 6, compared with about 40 for the attractive modes. The main reason for this is the somewhat less than optimum design for repulsion. Figure 10 illustrates the calculated magnetic field in the gap. For the attractive case (solid curve), the magnetic field is over 2 T at the center of the pole in the region of the vanadium permendur magnetic pole. For the repulsive case (dotted curve), the field under the soft magnetic pole is very small, and rises to a maximum of less than 1 T in the region away from the pole.

Figure 11 compares the calculated, normalized performance of the attractive and repulsive system (all the forces are divided by the attractive force at minimum gap). Although it is only in the region below 15 cm gap that the repulsive force differs significantly from the attractive force, this is not of much practical use because the forces at this point are of the order of 0.01 times the maximum value. If the attractive case at a minimum gap to 1.0 cm is considered, i.e., a lift to weight ratio approaching 40, then a relative force of 0.1 represents a lift to weight ratio of 4. If we take this as a lower value, comparable to a superconducting system, a permanent magnet attractive system could operate at gaps of about 9 cm. The corresponding gap for a repulsive system is approximately 5 cm.

With regard to implementing the approach of magnets in the guideway, it is not necessary to have the highest performance, expensive materials in the guideway. The US Bureau of Mines has successfully demonstrated a system with lower performance and cost ferrite permanent magnets in the guideway.¹⁰

Maglev System Optimization

Vehicles considered for magnetic suspension range from about 45,500 kg at 300 mi/hr for high speed ground transportation¹¹ to 230,000 kg to 360,000 kg at 600 mi/hr for magnetically-assisted launch space vehicles¹². The two permanent magnet arrays built for the wiggler are capable of lifting nearly all anticipated high speed ground vehicles, and 13 to 20% of the magnetically-assisted launch space vehicle at the minimum gap.

The availability of essentially full size individual permanent magnet components with high lift-to-weight capability is a significant milestone for the demonstration of full scale permanent magnet suspension systems. However, optimization of system

performance and costs must be carried out that includes adequate consideration of the guideway and system dynamics over the required range of velocities. For stability, the suspension must have at least four locations to support the vehicle on the guideway. These supports must be able to handle 25% of the vehicle weight plus dynamic loads.

An alternate is a system having eight suspension locations that handle 12.5% of the total load. The cross section for this guideway is considerably smaller. The optimization carried out under the National Maglev Initiative for a high speed 44,000 kg transportation vehicle resulted in a large number of magnetic supports¹³. The lift-to-weight ratio of the superconducting levitators for the optimum system was significantly lower than that required with four high lift levitators.

Control coils will probably be required to varying extents depending on the system. The repulsive systems are stable vertically, however, control may be required to provide adequate ride quality for passengers, or to limit the maximum dynamic loads in other instances. Attractive systems have a negative spring constant and control coils are required to counter this effect. In addition the control system, as well as other system elements that influence dynamics, must provide for acceptable overall system dynamic performance.

Magnetic systems using permanent or superconducting magnets have essentially no loss. As a result, these systems have no damping. This must be taken account of in overall system design.

SUMMARY

The design and construction of a unique wiggler magnet for the Stanford Synchrotron Radiation Laboratory has been described. All critical design parameters were met or exceeded. The high magnetic forces achieved in this system demonstrate that permanent magnets have the potential for high performance in attractive suspension systems.

The particular wiggler configuration built works well for attractive systems, and compares well with superconducting systems. However, optimization is needed for repulsive mode operation. A periodic magnet array can also serve as part of a linear motor propulsion element. A non periodic array in the direction of motion may be beneficial if permanent magnets are part of the guideway.

The feasibility of utilizing permanent magnets for maglev application has been demonstrated at full scale. The potential advantages for maglev are reduced power consumption, relative to resistive systems, and no cryogenic requirements, relative to superconducting systems.

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TABLE I
DIMENSIONS AND WEIGHTS

Approximate Dimensions

Magnetic Structure

Individual Full Strength Pole

Height	21.4 cm
Width	21.8 cm
Along Beam	13.0 cm
Overall Length	214.5 cm

Overall Dimensions

Height	199 cm
Width	108 cm
Along Beam	220 cm
Beam Height from floor	106.7 cm

Weights

Weight of each full strength pole	36.4 kg	(80 lbs.)
Assembled Magnetic Structure *	602 kg	(1325 lbs.)
Backing Beam*	367 kg	(806 lbs.)
Magnetic Structure with backing beam*	970 kg	(2131 lbs.)
<u>Total System</u>	3295 kg	(7250 lbs.)

** Weights of one assembly
- Two required one upper and one lower*

TABLE II
MAGNETIC CHARACTERISTICS

Characteristic	
Period Length (λ)	26 cm
Number of full-strength periods	7.5
Integrated field for each full-strength pole at 2.1 cm	17.816 T-cm
Length of each half-strength end pole	9.83 cm
Integrated field for each half-strength pole at 2.1 cm	8.902 T-cm
Width	21.8 cm
Total Length	214.5 cm
Minimum gap	2.100635 cm
Maximum gap	22 cm
On-axis peak field at minimum pole gap	2.0428 T
On-axis pole-to-pole peak field variation at min. gap	0.48%
Integrated field rolloff at min. gap (+/- 2.8 cm transverse offset)	3.79% Max.
On-axis peak field at maximum gap	1466 G
Relative integrated field strength of untuned end poles	50 +/- 0.33%

TABLE III
Maximum Performance Estimate for Permanent Magnet (PM) Arrays
For Vehicle Application

	<u>Weight</u> <u>(kg)</u>	<u>Force (kN)</u>	<u>Gap (cm)</u>	<u>Lift-to-weight</u> <u>Ratio</u>
One PM array in vehicle Attracted to PM in guideway	602	228	2.1	38.6
Two PM arrays in vehicle Attracted to ferromagnetic guideway	1204	456	1.05	38.6
One PM array in vehicle repulsed by P.M. in guideway	602	34.5	2.1	5.85
Two PM arrays in vehicle repelled by conductive guideway	1204	69	1.05	5.85

Lift-to-weight - Force (kN)/[Weight (kg) g (m/sec²)]

LIST OF FIGURE CAPTIONS

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Fig. 10 Magnetic Field at a Gap of 2.1 cm
Fig. 11 Relative Force as a Function of Gap for Attractive and Repulsive
Magnetic Systems

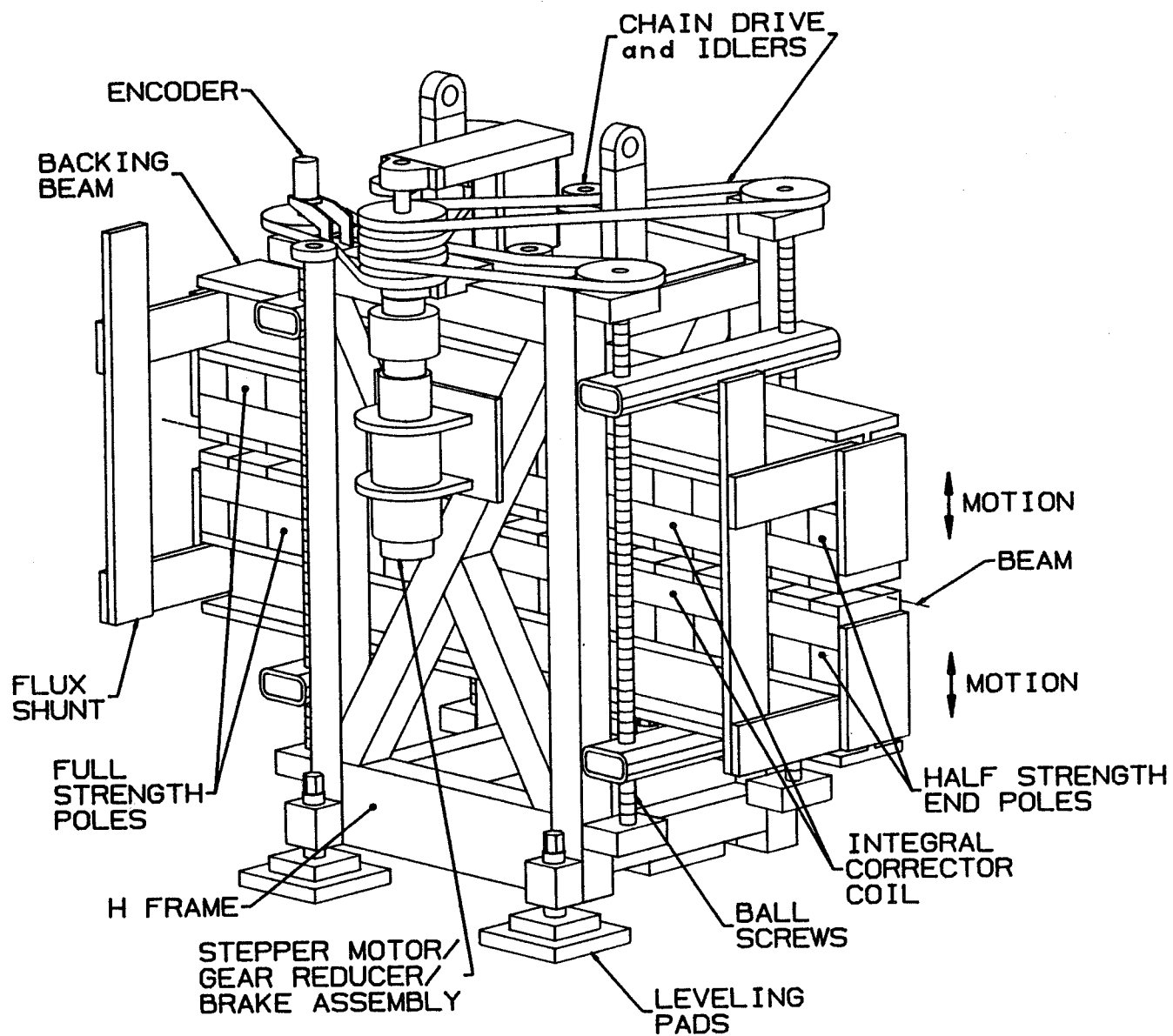


Figure 1

2.04 T SSRL Beamline 9 Wiggler Schematic

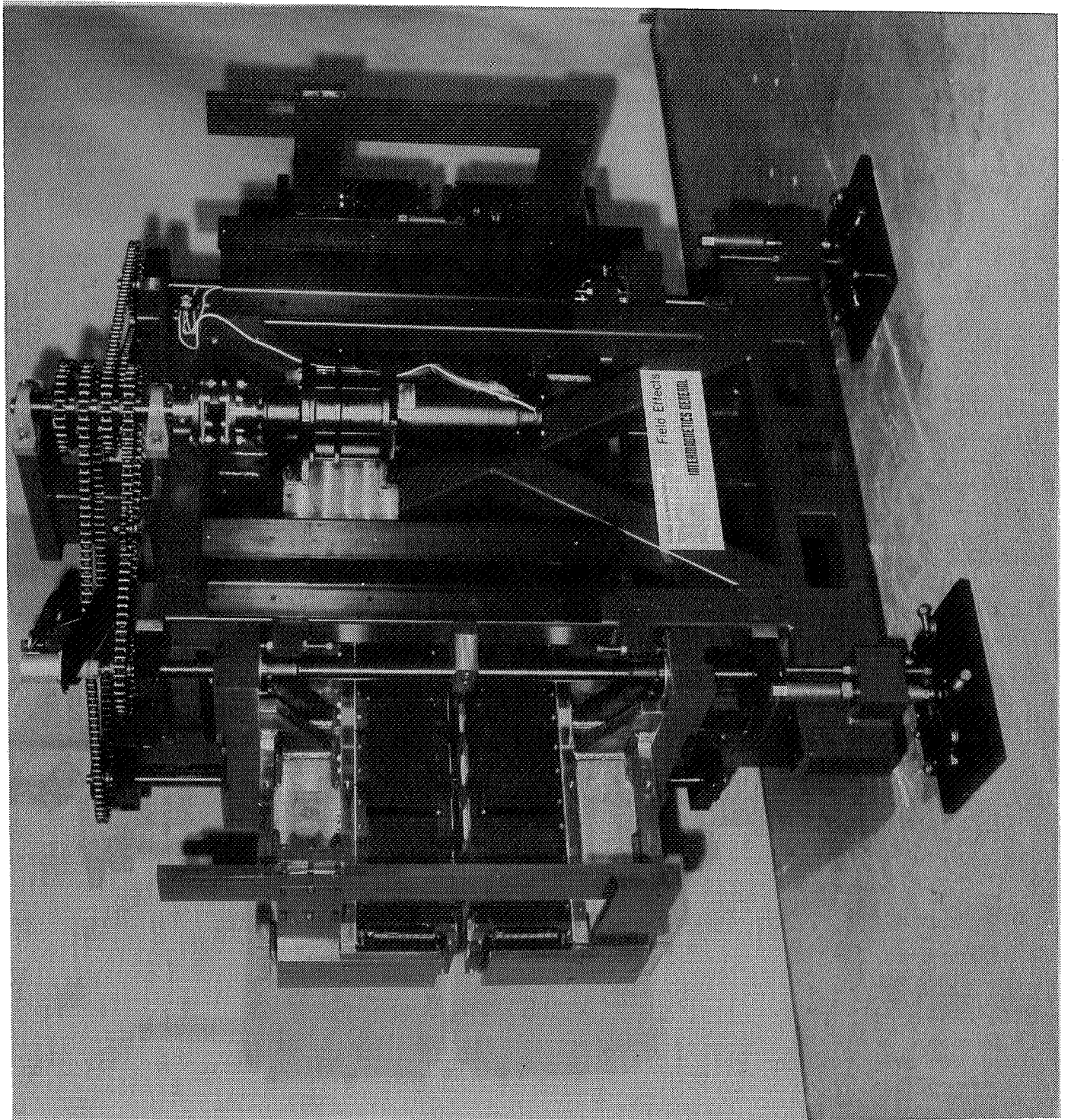


Figure 2
2.04 T Beamline 9 Wiggler

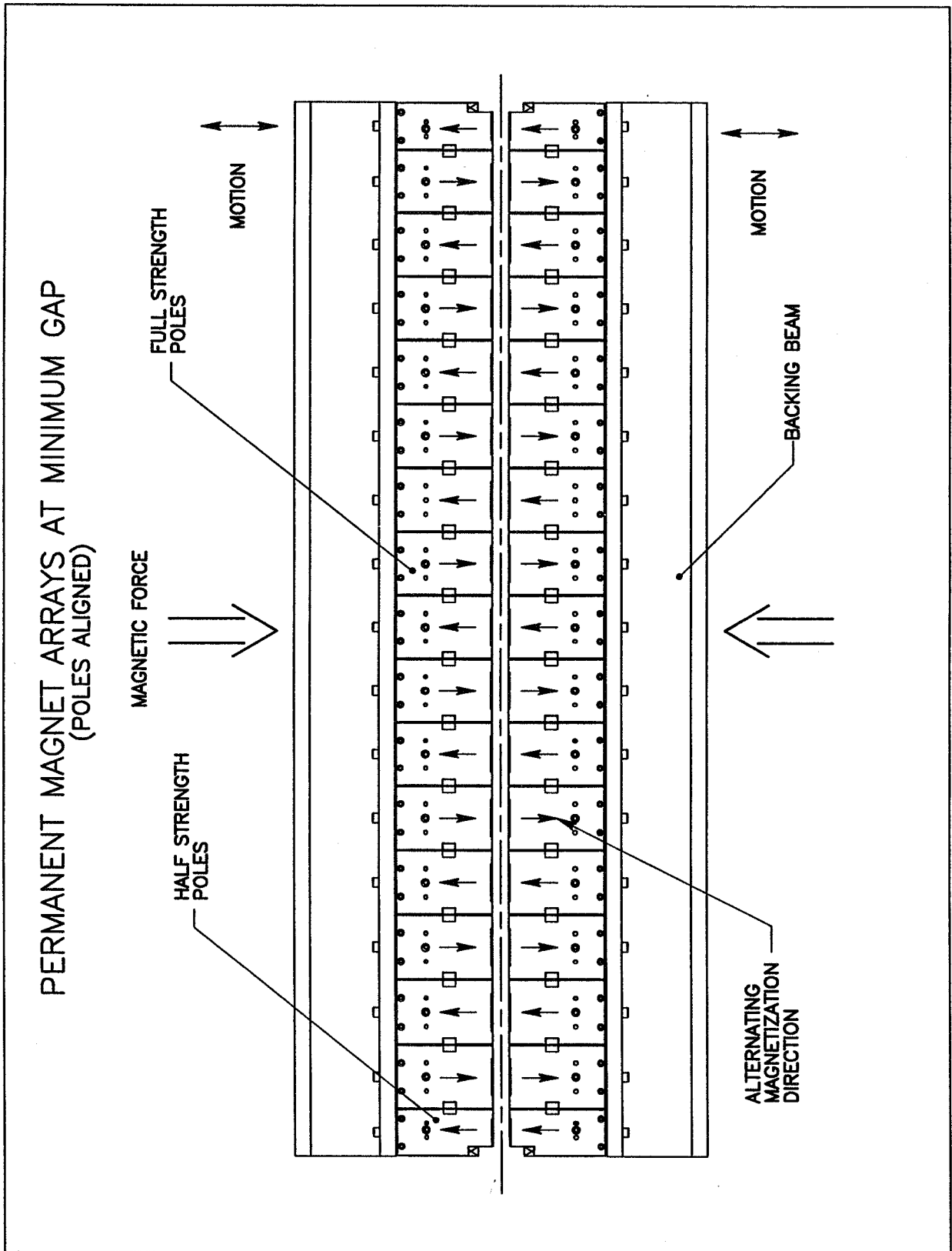


Figure 3
 Permanent Magnet Arrays at Minimum Gap (Poles Aligned)

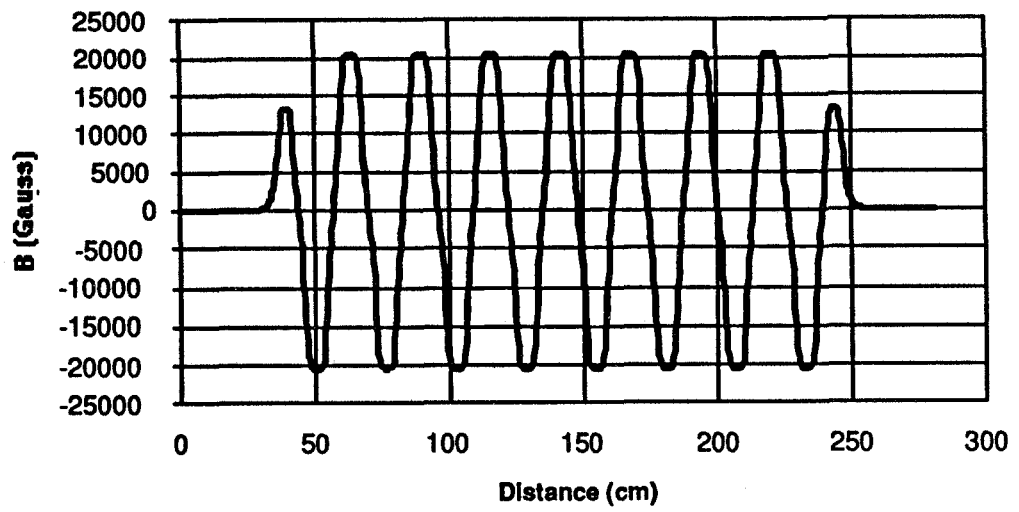


Figure 4a
Wiggler Corrected Magnetic Field Parallel to the Beam

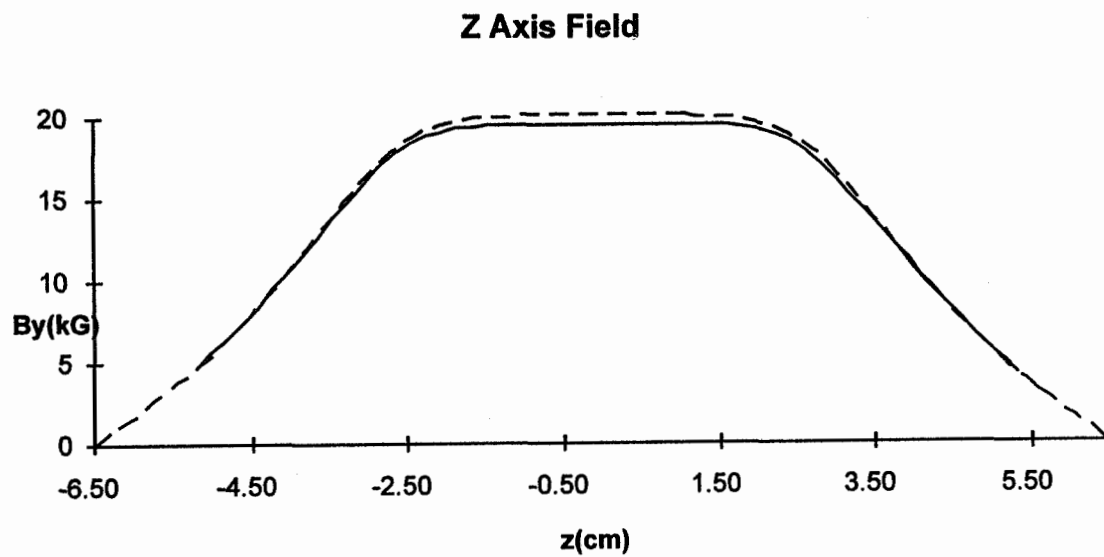


Figure 4b
Comparison of Measured (solid) to Computed (dashed) Wiggler On
Axis Field for One Half Period

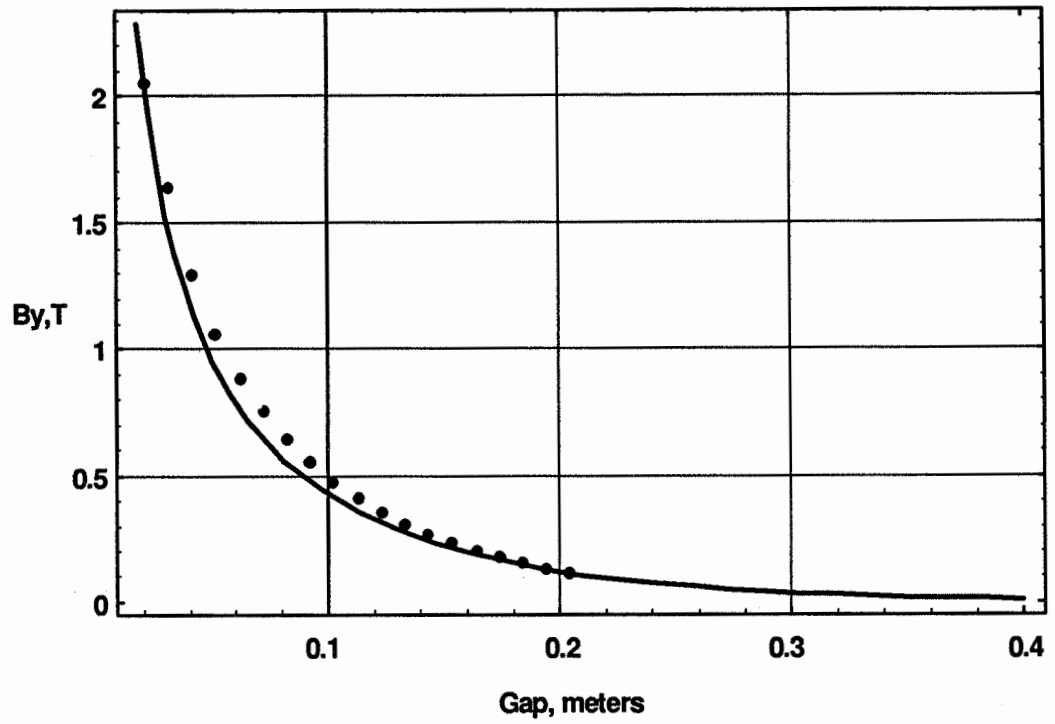


Figure 5
 Comparison of Predicted (solid), to Measured (dots)
 Wiggler Peak on Axis Field in the Gap

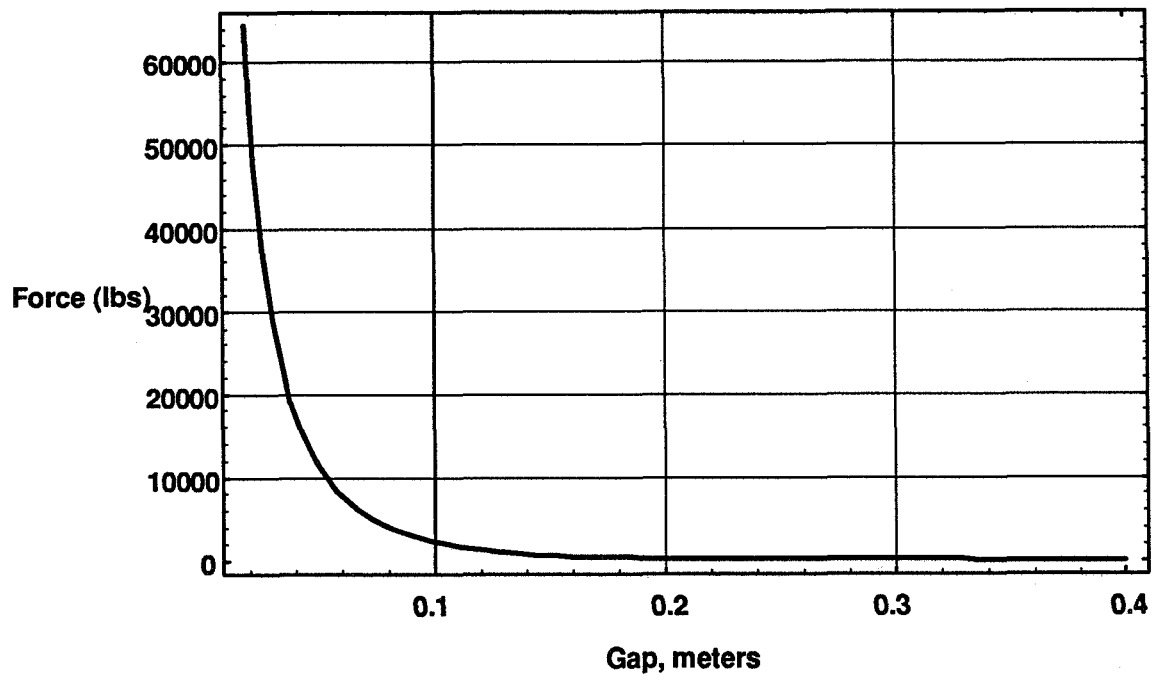


Figure 6
Predicted Wiggler Magnetic Force as a Function of Gap

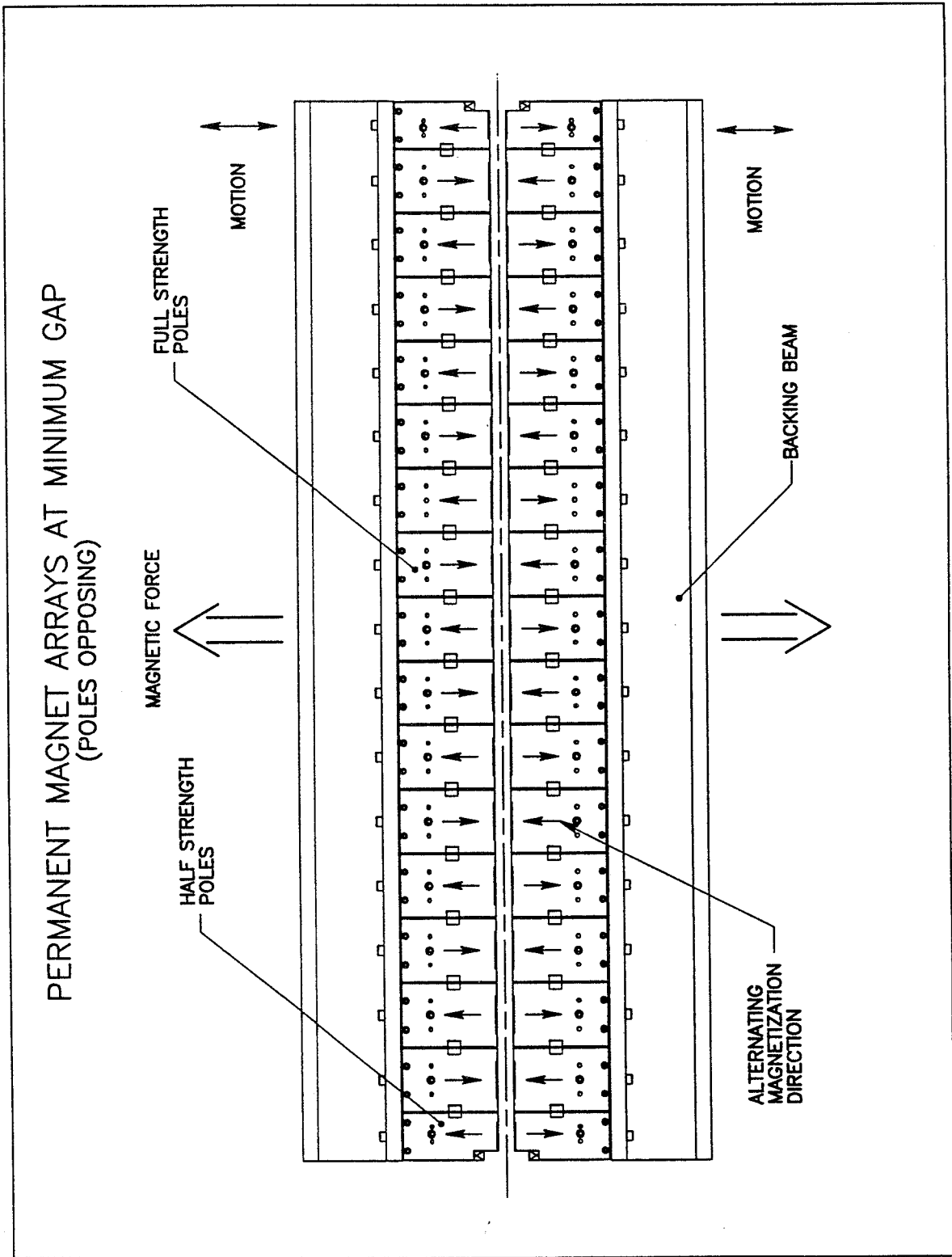


Figure 7
Permanent Magnet Arrays at Minimum Gap (Poles Opposing)

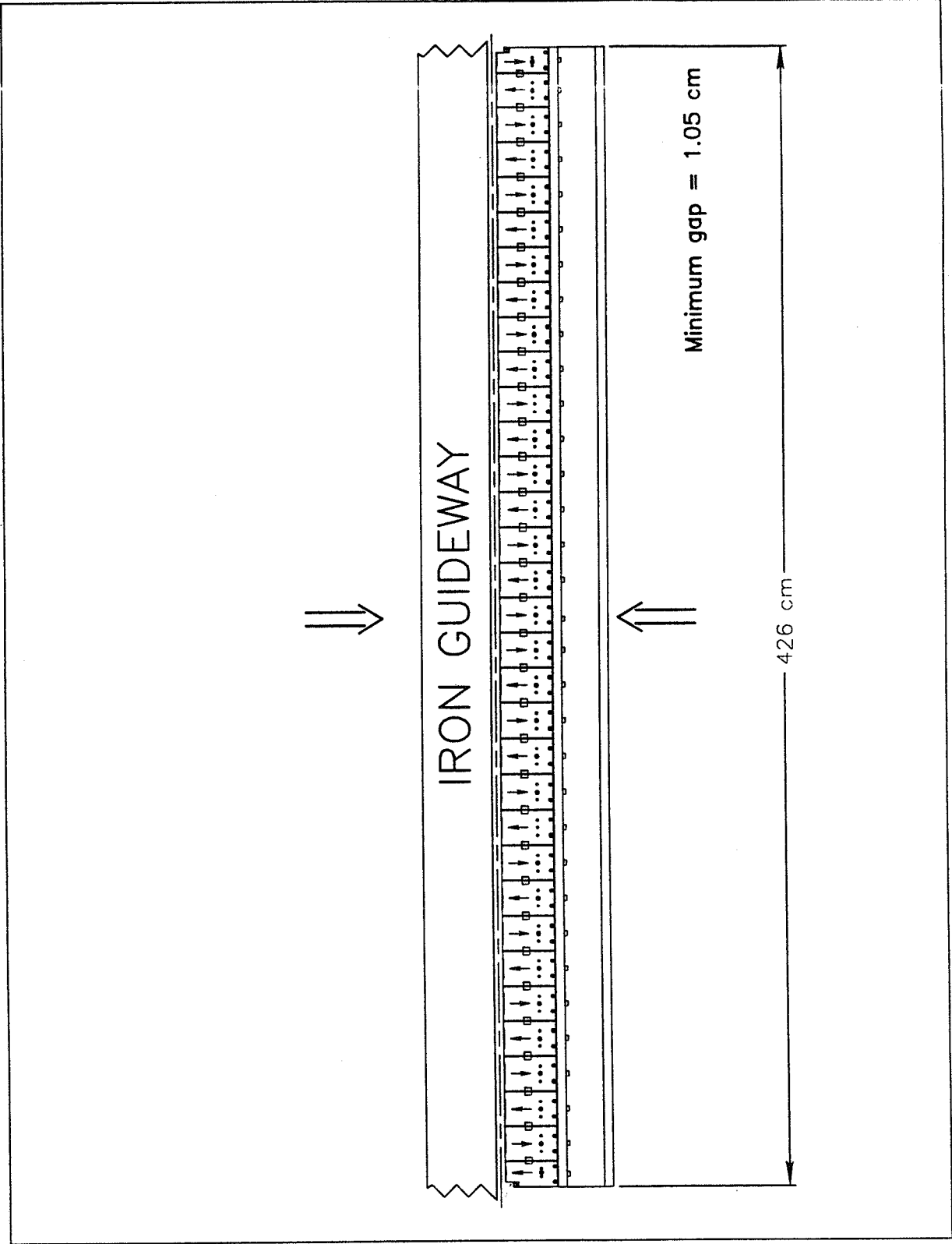


Figure 8

Permanent Magnet Arrays Attracted to Iron Guideway

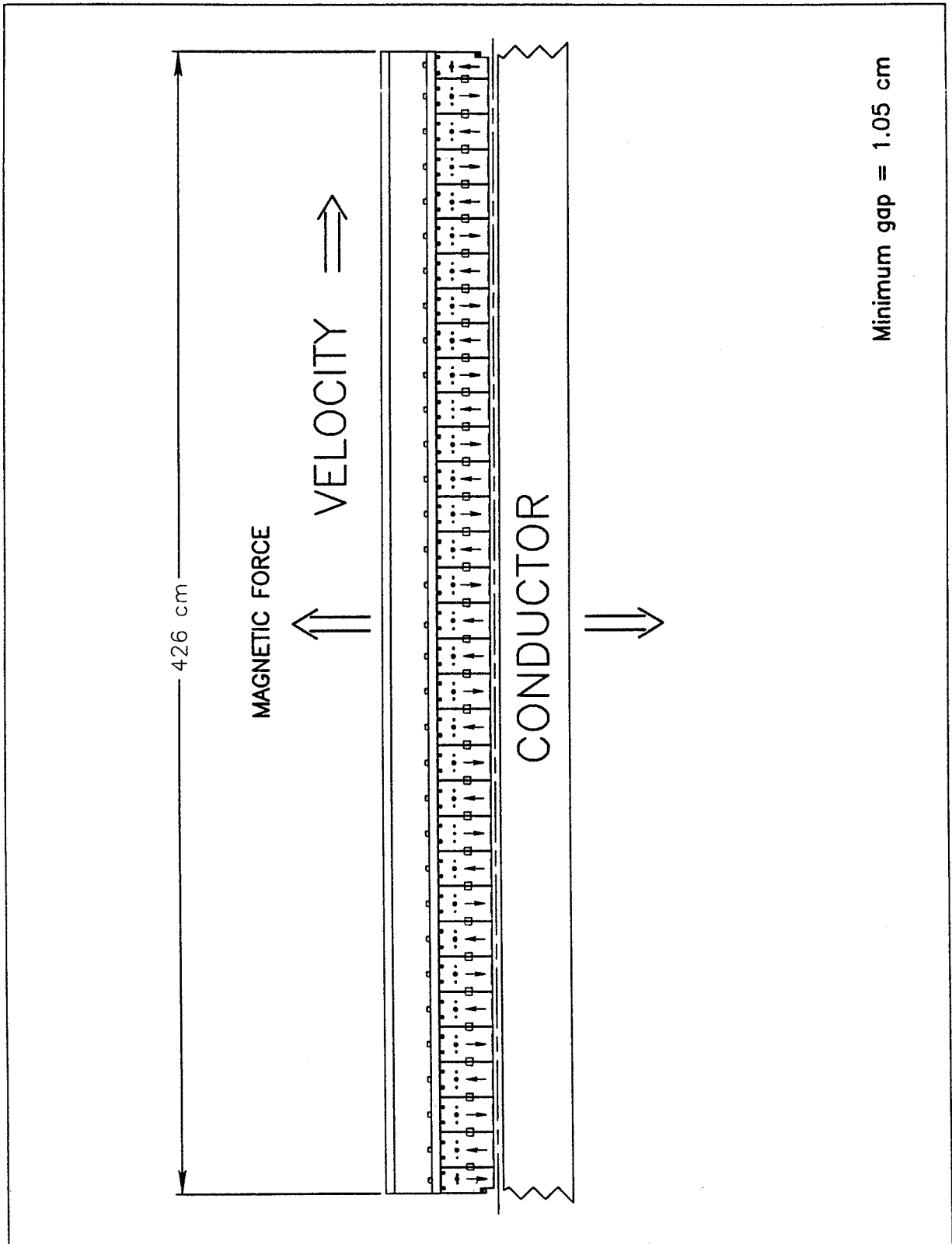


Figure 9

Permanent Magnet Arrays Repelled by Conducting Guideway

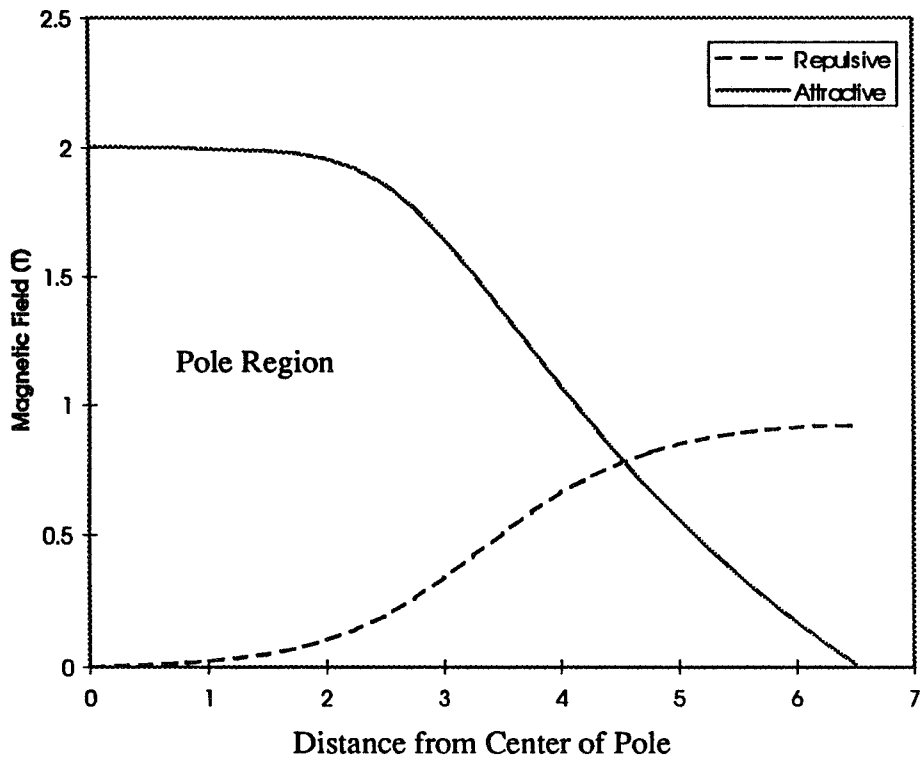


Figure 10
Magnetic Field at a Gap of 2.1 cm

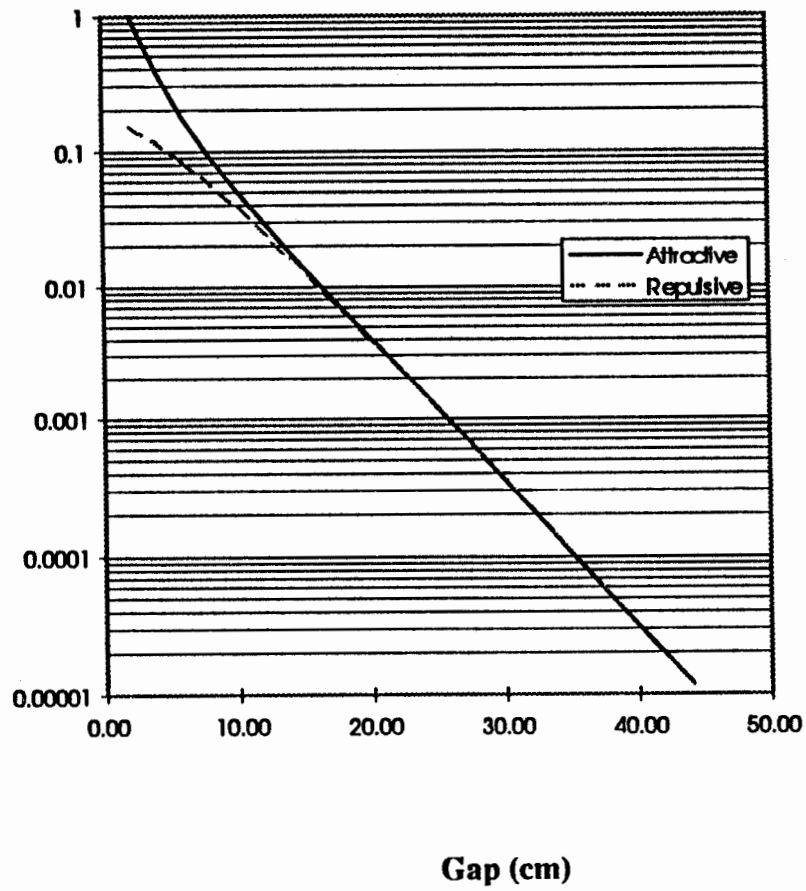


Figure 11

Relative Force as a Function of Gap for Attractive and Repulsive Magnetic Systems