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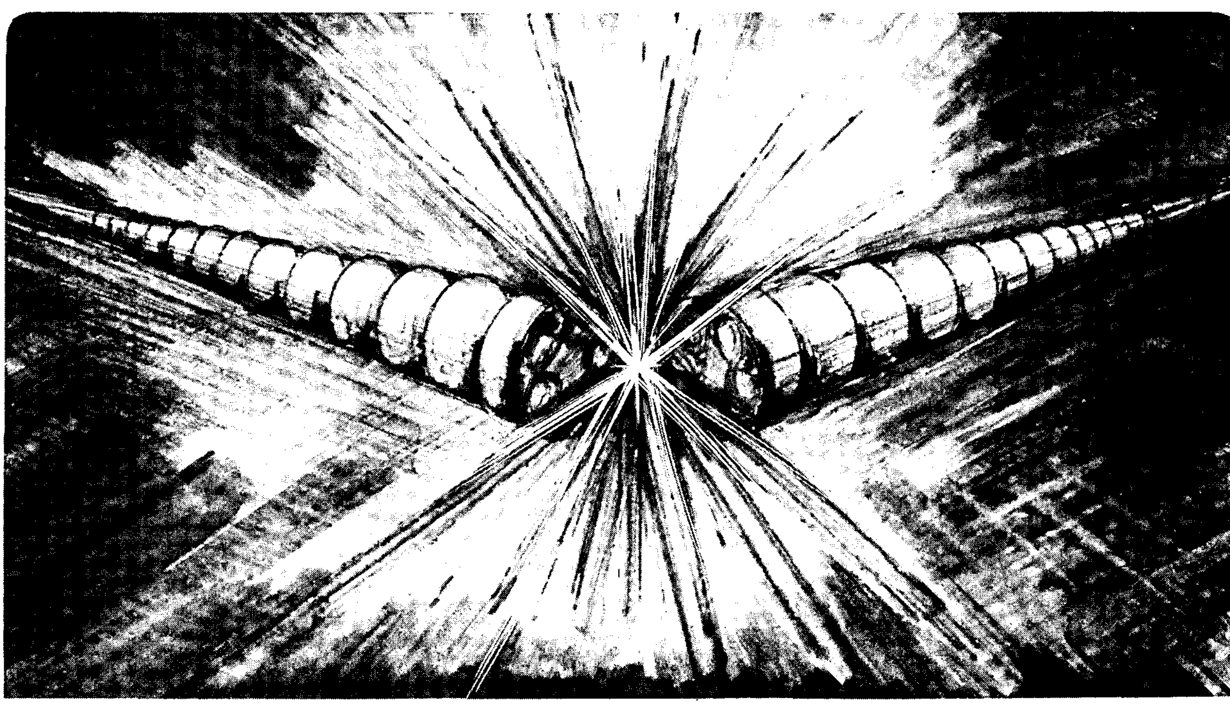

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ISOCHRONOUS BEAMLINES FOR FREE ELECTRON LASERS*

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Isochronous Beamlines for Free Electron Lasers

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Abstract

The transport systems required to feed a beam of highly relativistic electrons into a free electron laser have to satisfy very stringent requirements with respect to isochronicity and achromaticity. In addition, the line has to be tunable to match different operating modes of the free electron laser.

Various beamlines emphasizing different aspects, such as quality of isochronicity and achromaticity, simplicity of the design, and space configurations are shown and compared. Solutions are presented having time resolution in the range of 2 to less than 0.5 picoseconds for one percent of energy spread.

1 Introduction

In the framework of the proposed Combustion Dynamics Facility at Lawrence Berkeley Laboratory [1], a tunable infrared free electron laser is planned. The energy of the electrons produced by the LINAC will range from about 25 to 50 MeV, and they will occupy a phase-space area of about 0.4 x 0.5 mm-mrad in both the vertical and the horizontal directions. The energy spread of the system is about 0.5 %.

These electrons have to be transported from the LINAC to the undulator of the laser in which they have to travel parallel with the light. In order not to interfere with the optical mirrors of the laser, the beam has to be offset horizontally from the accelerator axis to the light axis. The schematic layout of a free electron laser is shown in Figure 1.

Inside the optical cavity, the electron and light beam bunches must overlap horizontally and vertically as well as longitudinally. In order not to disturb the lasing process, it is very important that overlapping does not change over time. In particular, it should not be affected by the energy jitter of the LINAC, which is in the order of 0.05 %.

The horizontal independence of bunch shape can be achieved with an achromatic system. The longitudinal stability requires isochronicity; in particular, the flight time should not depend on the electron's energy. To be specific, linear time of flight effects should be less than 2 psec per 1 % relative difference in energy. This is necessary because the 0.05 % energy fluctuation must not cause a time fluctuation greater than 0.1 psec.

Besides these boundary conditions, there are geometric limitations. The offset should be large enough to not interfere with the optical mirrors. In addition, the length of the transport system should not exceed about 7m. Furthermore, the high energy of the electrons, which entails a maximum rigidity of 0.168 Tm, limits the bending radii of magnets to about 30 cm in order to stay in the .5 Tesla regime.

The high energy of the electrons entails that since the particles move essentially with the speed of light, energy differences do not translate into velocity differences, and thus drift regions and non-bending elements do not introduce time of flight effects. The only time of flight terms come from bending elements and later cross coupling.

2 Achromaticity and Isochronicity

In this section we will discuss the achromaticity and isochronicity requirements of the system. The study and understanding of achromatic systems is almost as old as particle optics [2, 3]. A system is called achromatic if to first order, the final trajectories after the system do not depend on the energy of the particle. Using the standard notation for transfer matrix elements, this means

$$(x, d) = (a, d) = 0. \tag{1}$$

If only $(x, d) = 0$ at a certain point, a system is called dispersion free at that point. Note that achromaticity is a global property that holds over at least a field free region, while being dispersion free is a local property that holds at only one point.

There are numerous ways to design achromatic systems [2, 3], and also higher order achromats are known [4, 5]. One can easily see [2] that achromaticity in a bending system requires at least two bending magnets. They are arranged in such a way that their chromatic effects cancel.

As discussed in the previous section, FEL beamlines do not only have to be achromatic, but they also have to preserve the timing of the bunches very accurately. This means that in addition to the requirements of achromaticity, we must satisfy the first order conditions

$$(t, x) = 0 \tag{2}$$
$$(t, a) = 0 \tag{3}$$
$$(t, d) = 0 \tag{4}$$

or at least minimize the terms according to the above requirements. Isochronous systems have also been studied long ago, and it was soon concluded that an isochronous bending system has to contain at least three bending magnets [2]. An important fact for the design of isochronous systems comes from the symplectic structure of phase space maps. In [6] we showed that symplecticity entails interconnections between matrix elements. In particular, one obtains in the case of midplane symmetry that

$$\begin{aligned}(t,x) &= F\cdot[(x,x)(a,d)-(a,x)(x,d)] && (5)\\ (t,a) &= F\cdot[(x,a)(a,d)-(a,a)(x,d)] && (6)\end{aligned}$$

where the factor F only corrects for the usual scaling of the variables [7, 8]. This entails that an achromatic system automatically satisfies $(t,x) = (t,a) = 0$. Thus the only time of flight term causing lack of isochronicity is the term (t,d). To second order, the situation is similar. Symplecticity entails that

$$\begin{aligned}(t,xx) &= F\cdot[(x,x)(a,xd)-(a,x)(x,xd)+(x,xx)(a,d)-(a,xx)(x,d)]\\ (t,xa) &= F\cdot[(x,x)(a,ad)-(a,x)(x,ad)+(x,xa)(a,d)-(a,xa)(x,d)]\\ (t,xd) &= F\cdot[(x,x)(a,xd)-(a,x)(x,dd)+(x,xd)(a,d)-(a,xd)(x,d)]\\ (t,aa) &= F\cdot[(x,a)(a,ad)-(a,a)(x,ad)+(x,aa)(a,d)-(a,aa)(x,d)]\\ (t,ad) &= F\cdot[(x,a)(a,dd)-(a,a)(x,dd)+(x,ad)(a,d)-(a,ad)(x,d)]\\ (t,yy) &= F\cdot[(y,y)(b,yd)-(b,y)(y,yd)+(x,yy)(a,d)-(a,yy)(x,d)]\\ (t,yb) &= F\cdot[(y,y)(b,bd)-(b,y)(y,bd)+(x,yb)(a,d)-(a,yb)(x,d)]\\ (t,bb) &= F\cdot[(y,b)(b,bd)-(b,b)(y,bd)+(x,bb)(a,d)-(a,bb)(x,d)]. && (7)\end{aligned}$$

So the only "free" second order time of flight term is (t,dd). Note that from these equations it follows that all time of flight matrix elements from (t,xx) through (t,bb) vanish for a second order achromat. Thus, a second order achromat that satisfies $(t,dd) = 0$ is isochronous.

In the next section we will show three different solutions for achromatic beamlines which meet the isochronicity requirements presented in the previous section. The systems differ in simplicity, geometric layout, and degree of isochronicity. Note that the phase space volume is so small that most of the time higher order effects do not have to be corrected. Especially in the case of the fully isochronous system, however, it is necessary to choose the parameters of the systems such that second order effects stay within bounds.

The calculations have been performed with COSY INFINITY [9, 10, 11] and COSY 5.0 [8, 12, 13]; because of the phase space parameters, the high-order features of these programs are not needed, and any other design code [14, 15, 16, 17, 18] could have been used. However, the powerful input language of COSY INFINITY allowed very efficient and flexibles optimization strategies consisting of nested optimizations and manual tuning without ever leaving the program.

3 A Simple Four Magnet Achromatic Beamline

In this section we will show a simple achromatic beamline consisting only of four $n = 1/2$ bending magnets. The system is not fully isochronous, the term (t, d) is not corrected. However, since the left over term is usually quite small, the system can be used in practice. In the next section we will present a system with the same flavor, in which, however, the term (t, d) is also corrected.

The four cell system consists of identical combined-function magnets that are placed in series like a double S, where each of the magnets is preceded and followed by an identical drift. The length of the drift is chosen such that the subsystem drift-magnet-drift performs parallel-to-point imaging.

When two such cells are placed behind each other in a mirror-symmetrical way, bending in opposite directions, the resulting two-cell system is dispersion-free and produces unmagnified x and y images. Furthermore, (t,a) vanishes automatically. When two of these two-cell systems are placed in series, the transfer matrix becomes unity in the horizontal and vertical planes, and in particular the system is fully achromatic. Thus, all of the linear time of flight matrix elements but (t, d) vanish. So we have to search parameters for the system that make (t, d) small enough.

It turned out that the value of (t, d) is roughly proportional to the total horizontal offset of the system. So the smaller (t, d) has to be chosen, the smaller the total offset becomes. The following parameters describe a system that produces a total offset of about 18 cm and has an isochronous defect of almost 2 psec per percent of energy spread.

Drift	length 1.702 m		
Bending Magnet	radius 0.4 m,	angle 26 degrees,	inhomogeneity 0.5
Drift	length 0.1m		

This system has the following linear transfer map:

$$\begin{pmatrix} 1 & 2.104 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 2.104 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & -0.0561 \end{pmatrix} \tag{8}$$

Figure 2 shows some characteristic rays going through the system, and Figure 3 shows the total time of flight aberrations as a function of position in the system. Unfortunately, the maximum total offset of about 18 cm for the required time of flight aberrations is very tight, imposing restrictions on the fabrication and mounting of the optical mirrors.

4 A Fully Isochronous Beamline

In this section, we discuss a system with a similar flavor as the one discussed in the previous section. However, by using additional quadrupoles, full first order isochronicity is achieved.

The general layout of the system is again a double S arrangement. Furthermore, the second and fourth cells are mirror images of the first and third cells. Instead of a combined function magnet we here use a dipole. The cell is point-to-parallel in the x direction, which means that the matrix element (a, a) vanishes. There are no special requirements for the y motion, except that it should stay well contained. These two requirements can be achieved easily by using two quadrupoles before the bending magnet.

We also demand that, after two cells, the chromatic time of flight term (t, d) must vanish. This can be achieved by placing a suitable quadrupole in the center between the bending magnets.

Again, after four cells arranged as a double S, the matrix in the x direction becomes unity, so the system is fully achromatic to first order. Furthermore, because (t, d) vanishes for each double cell, it also vanishes for the whole system. Thus the system is fully isochronous. The linear matrix in the y plane is not unity; the quadrupoles are merely chosen such that its elements stay well contained. The parameters of the elements in each cell are as follows:

Drift	length 100 cm		
Quadrupole	length 20 cm,	aperture 3 cm,	strength 0.07946 T
Drift	length 15 cm		
Quadrupole	length 20 cm,	aperture 3 cm,	strength -0.07000 T
Drift	length 15 cm		
Bending magnet	radius 0.04 m,	angle 45 deg,	homogenous
Drift	15 cm		
Quadrupole	length 20 cm,	aperture 3 cm,	strength 0.05561 T

The bending angle of 45 degrees corresponds to a strength of the central quadrupoles (located between the dipoles) that is not excessive. The focal length of the cell is chosen to be about 2 m to satisfy the geometrical requirements. Given the bending angle and the focal length, narrow bounds result for the bending radius and therefore the strength of the dipole field. In our solution the strength of the dipole field turns out to be moderate with less than 0.5 T.

After the strength of the central quadrupole was determined, the strengths of the quadrupoles upstream from it were chosen such that the cell is point-to-parallel and has an acceptable y displacement. The system has the following linear transfer matrix:

$$\begin{pmatrix} 1 & 11.035 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0.54080 & 1.3362 & 0 \\ 0 & 0 & -0.52952 & 0.5408 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{9}$$

Figure 3 shows the trajectories of several principal rays through the system. It can be seen that the first bending magnet introduces chromatic effects that disappear again after the last bending magnet. Figure 4 shows the sum of absolute values of the time of flight aberrations. All of these aberrations vanish after the last dipole.

5 A More Involved Two Magnet Beamline

In this section, we will present an achromatic system based on a different approach that is not fully isochronous, but the remaining (t, d) is very small. It will turn out that for the required offset, this system has a much smaller (t, d) than the one discussed in section 3. The system has a rough similarity with the one proposed in the FELIX study [19], but outperforms it as far as beam sizes and time of flight aberrations are concerned.

The system consists of a mirror symmetric arrangement of two identical cells. The cell consists of a drift of arbitrary length, followed by a bending magnet, and another drift in the middle of which a quadrupole is placed. The strength of the quadrupole is chosen such that the cell is dispersion-free after the second drift, i.e. $(x, d) = 0$. It is easy to see that a system consisting of two such cells placed in mirror symmetry and bending in different directions is achromatic. In order to be able to counterbalance the action of the two quadrupoles, a third quadrupole is placed in the center between them, and the strength of the two outer quadrupoles is readjusted accordingly.

The cell of the system has the following parameters:

Drift	length .2m		
Bending magnet	radius 0.5m,	angle 25 deg,	homogeneous
Drift	length 0.4 m		
Quadrupole	length 0.2m,	aperture 3 cm,	strength 0.10525 T
Drift	length 0.3m		
Quadrupole	length 0.1m,	aperture 3 cm,	strength -0.0850 T

This system has the following first order transfer matrix:

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 3.0662 & 6.6469 & 0 & 0 & 0 \\ 1.2640 & 3.0662 & 0 & 0 & 0 \\ 0 & 0 & 1.1801 & 2.0575 & 0 \\ 0 & 0 & 0.19086 & 1.1801 & 0 \\ 0 & 0 & 0 & 0 & 0.0129 \end{pmatrix} \tag{10}$$

The remaining time of flight term is about 0.4 picoseconds per percent of energy spread, certainly much below the requirement. Furthermore, the total offset of the system is about 95 cm, avoiding interference of the electron beam and the optical system.

6 Comparison of the three systems

In this section we summarize the details of the previous three sections and provide a direct comparison of the systems. The key quantities for the analysis of performance are isochronicity and offset. The price of the system is determined mainly by the number of components, so we list the required number of magnets and quadrupoles. We also give the maximum 1σ beam width which determines the size of the tube; because of radiation it is advisable to contain up to 4σ inside the pipe.

	System 1	System 2	System 3
number of magnets	4	4	2
number of quadrupoles	0	10	3
total offset	0.19 m	1.46 m	0.95 m
time of flight errors	2 psec / 1 %	0.1 psec / 1 %	0.4 psec / 1 %
maximum beam width	3 mm	6 mm	3 mm

7 Matching the Beam to the FEL

Besides the transport of the beam, the beamline also has to generate the proper shape of the beam inside the Undulator. The beam envelope in the x direction must be focused to a waist at the center of the undulator. The beta function at the waist, the ratio between the beam's size and its angular divergence, should be about 1 meter, i.e., half the undulator length. In the y direction, the beam envelope is focused to a waist at the beginning of the undulator, then maintains a constant value due to focusing by the alternating field of the undulator magnet. The value of the beta function in the y direction should be adjustable between about 0.25 m and 1.1 m.

This task is best decoupled from the rest of the system, and performed by a quadrupole triplet placed behind the beamline. Note that such quadrupoles have no effect on the achromaticity of the system; they also do not affect linear time of flight properties because the electrons are highly relativistic.

The strengths of the three quadrupoles are varied to achieve the different beta functions. For the second and third systems, solutions have been found for a variety of beta-y values between 0.3 and 1.1 m, requiring field strengths between 0.02 and 0.08 tesla.

8 Beam Diagnostics and Transport to the Beam Dump

After the electron beam has passed through the Undulator of the free electron laser, it has to be transported to a beam dump. Furthermore, it is desirable to be able to analyze the beam parameters. While the determination of the beam position is easily done using beam position monitors, it is important to have information about the beam's energy and time distributions. In particular, it is helpful to have 2 dimensional information in the form of an energy-time plot.

To achieve this goal, we propose a system similar to one used in Los Alamos [20]. It consists of a bending magnet acting as an energy separator combined with a fast deflector that deflects a beam bunch in the y direction. By sweeping the field of the deflector while a bunch travels through it, the vertical bending angle produced by the deflector that an electron experiences is a measure for the time at which it passed the deflector. Using this scheme, one can put a quartz screen at the image point of the separator magnet and read off the requested two dimensional picture with a camera.

The system we propose here has the following form:

Fast and	slow deflectors,	total length 0.8 m	
Bending magnet	radius 0.5m,	angle 90 deg,	n=.5
Drift	length 1.74m		
Drift	length 10 cm		
Quadrupole	length 0.2m,	aperture 3 cm,	strength .03 T
Drift	length 1m		

This system produces a stigmatic image after the 1.74m drift. At this point, the dispersion is such that a beam energy spread of .5 % corresponds to about 1 cm, a value similar to the one in the Los Alamos setup. The image point is followed by a short drift and a quadrupole which slightly focuses the off energy electrons. About 1 m behind the quadrupole is a good place for the beam dump. At this point, the beam has a diameter of about 5 mm and is approximately round.

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Figure captions

Figure 1: A schematic layout of a free electron laser.

Figure 2: A simple four cell combined function magnet achromat without quadrupoles and with a remaining time of flight aberration of about 2 psec.

Figure 3: The value of the total time of flight aberration as a function of position in the system of figure 2.

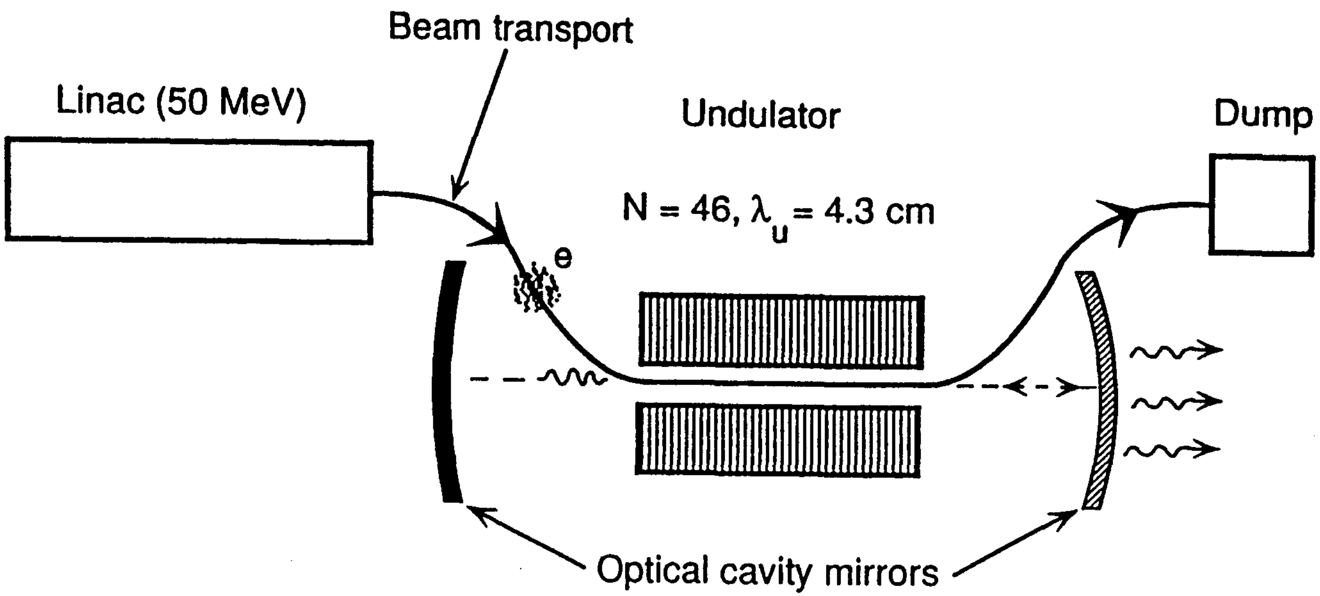
Figure 4: A more advanced 4 cell first order achromat which is also fully isochronous.

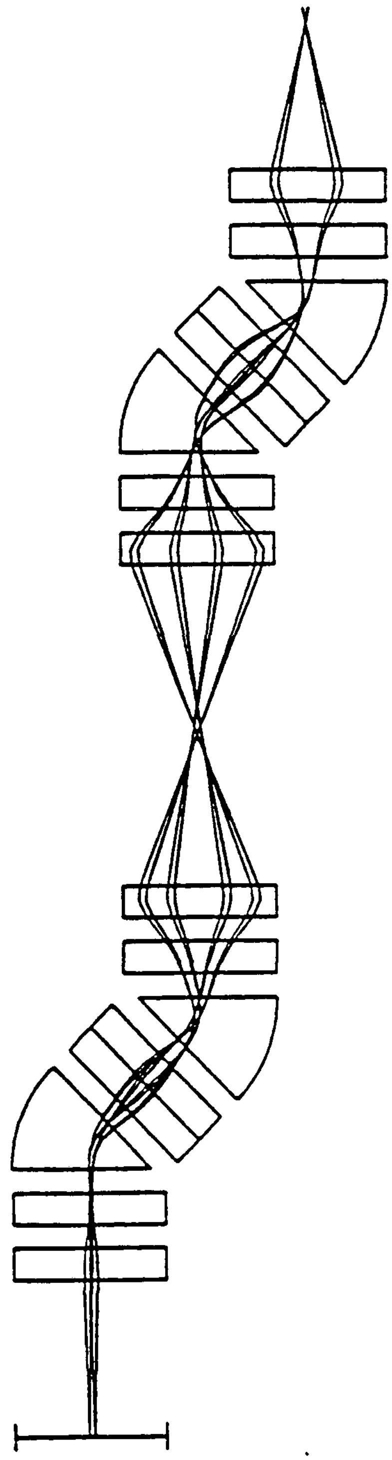
Figure 5: The value of the total isochronicity as a function of position in the system of figure 4.

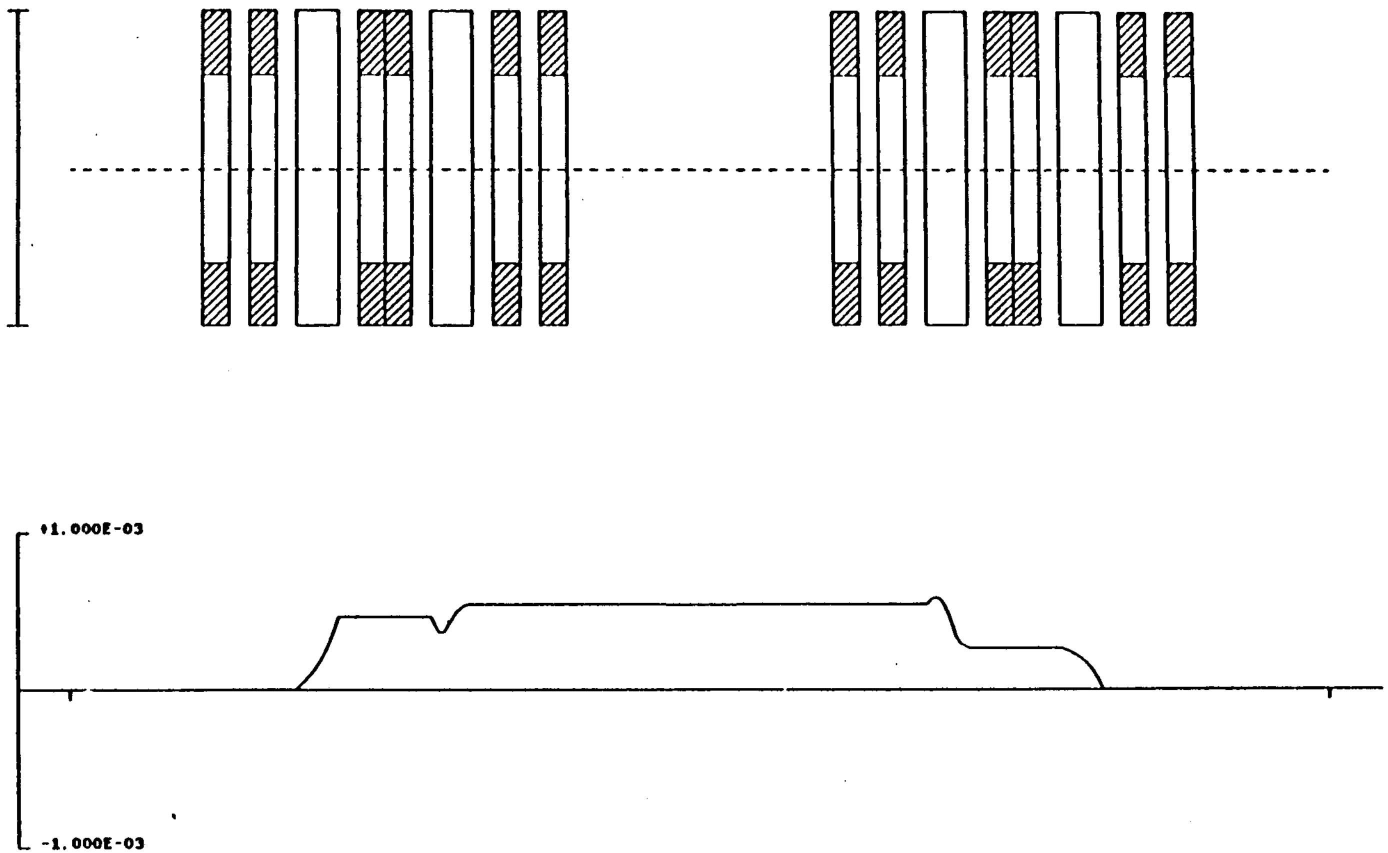
Figure 6: A relatively simple two cell achromat that has a very small chromatic time of flight distortion and provides a large horizontal offset.

Figure 7: The value of the total time of flight aberration as a function of position in the system of figure 6.

Schematic of an IRFEL







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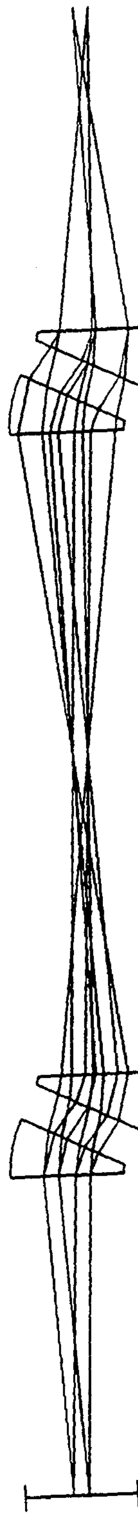

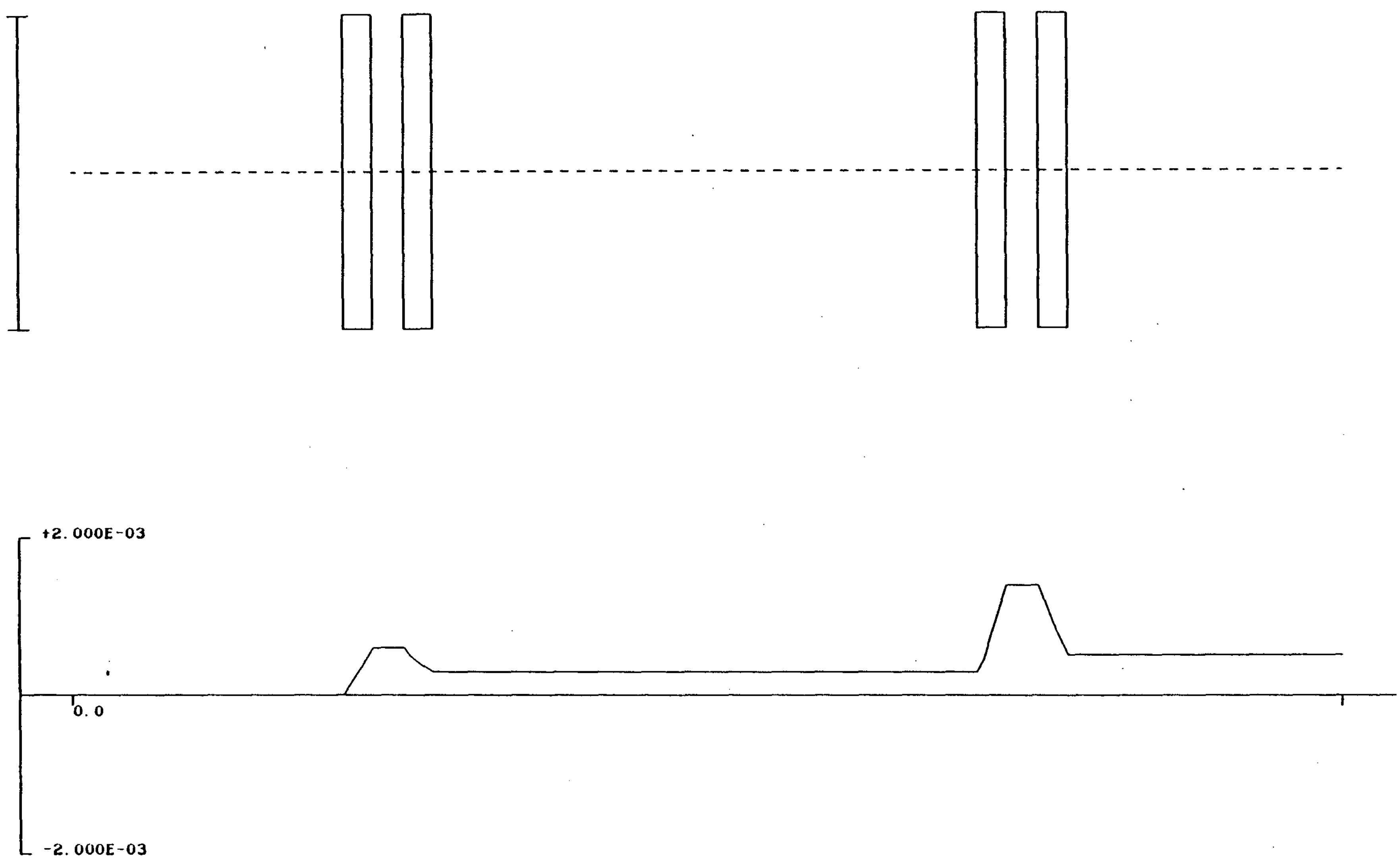
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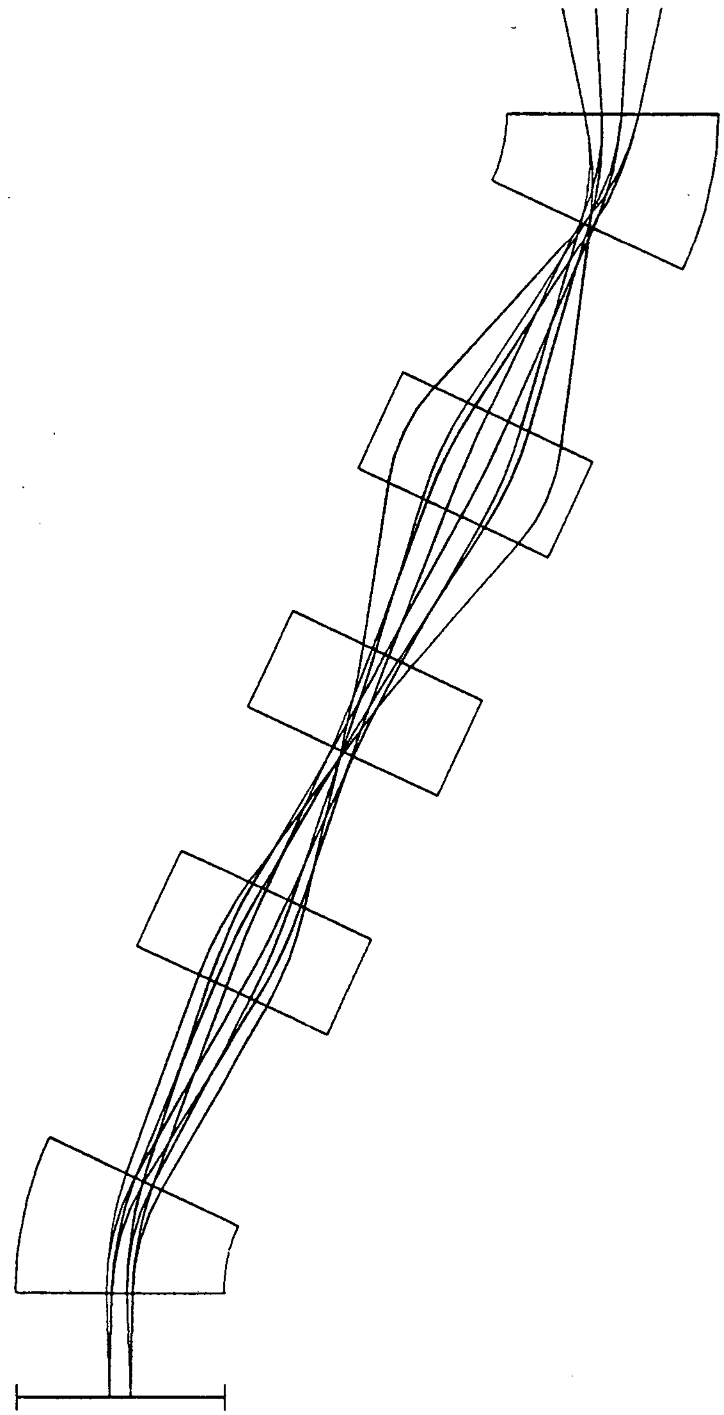

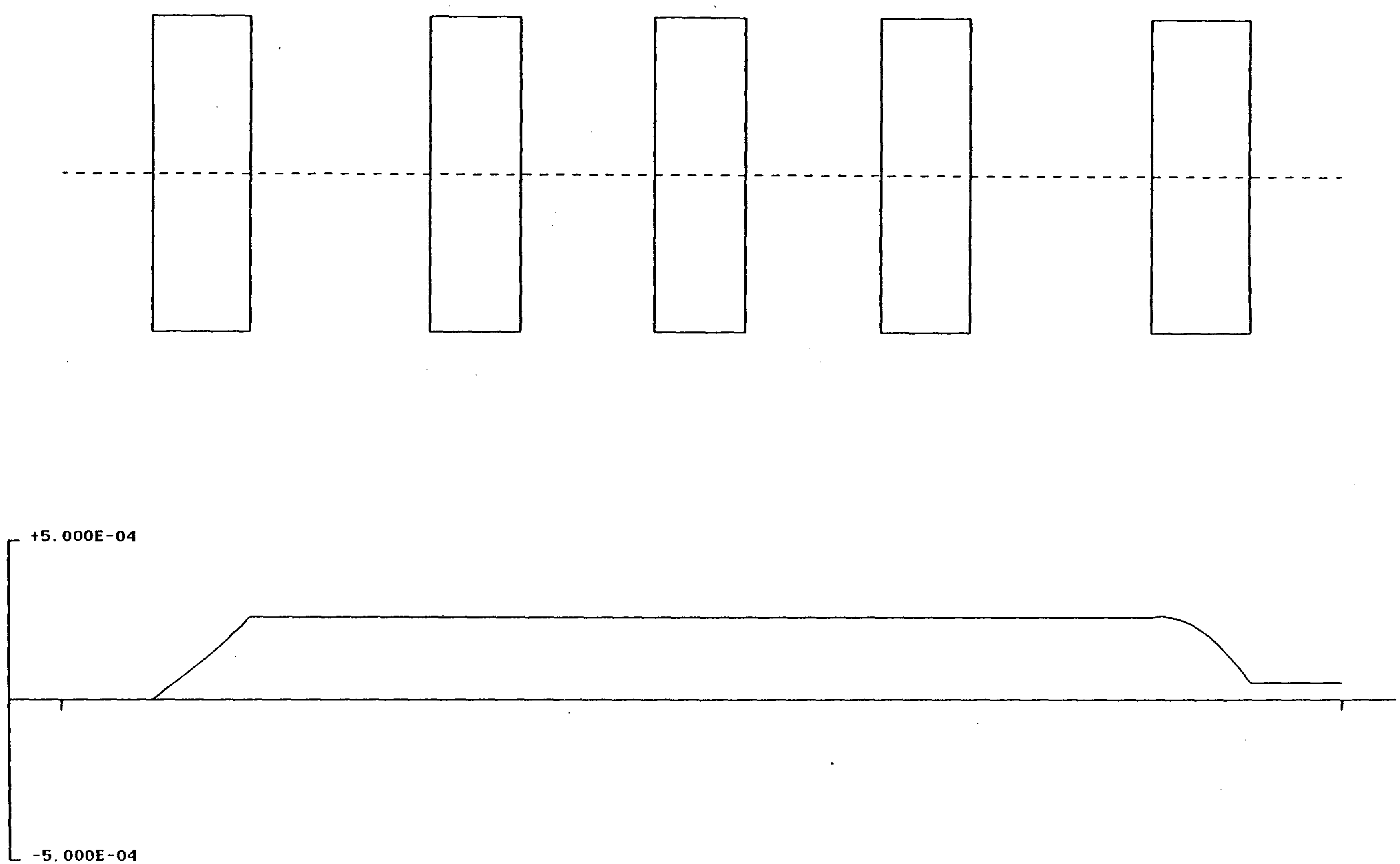
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