Title
Study of Magnetic Lattice for a Quasi-Isochronous Ring

Journal
Particle Accelerators, 44

Authors
Amiry, A.
Pellegrini, C.
Forest, E.
et al.

Publication Date
1993-08-01

LBL-34065
UC-414
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

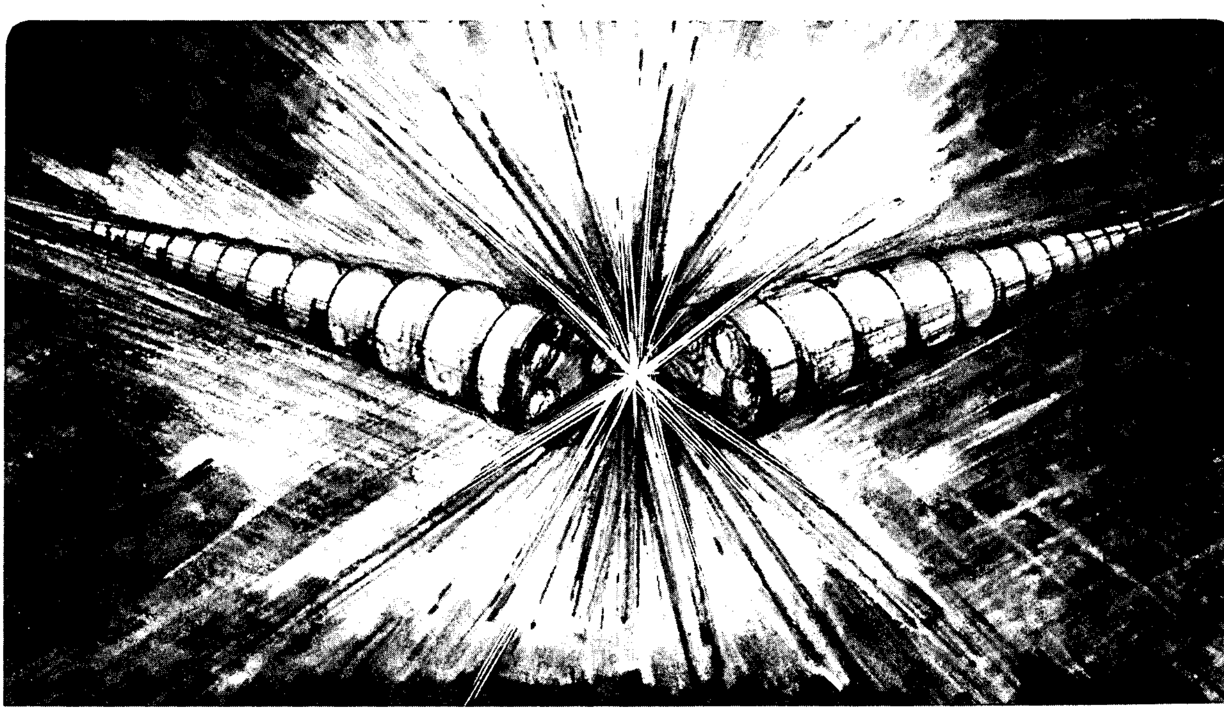
Accelerator & Fusion Research Division

Submitted to Particle Accelerators

Study of Magnetic Lattice for a Quasi-Isochronous Ring

A. Amiry, C. Pellegrini, E. Forest, and D. Robin

August 1993



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL-34065
CBP Note-018

"Study of Magnetic Lattice for a Quasi-Isochronous Ring"

Ali Amiry and Claudio Pellegrini

University of California at Los Angeles
405 Hilgard Ave
Los Angeles, CA 90024

Etienne Forest and David Robin

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Study of Magnetic Lattice for a Quasi-Isochronous Ring *

Ali Amiry and Claudio Pellegrini

University of California at Los Angeles

405 Hilgard Ave, Los Angeles, CA 90024

Etienne Forest and David Robin

Lawrence Berkeley Laboratory

1 Cyclotron Road, Berkeley, CA 94720

August 9, 1993

ABSTRACT

Quasi–Isochronous rings have been considered for electron–positron colliders to obtain a large luminosity with a small average beam current. This approach offers the advantage of minimizing vacuum and RF system problems, and multibunch instability effects. In this paper, we review the basic physics of a QIR, the condition for stable single particle motion, and the dynamic aperture. The collider we discuss is a Φ–factory with a single ring, and beam energy of 510 Mev. This ring uses a very strong focusing of the electron and positron beams at the interaction point, i.e. a beta function in the millimeter range; and a momentum compaction variable over a large range, of -0.008 to +0.005, to control the bunch length.It has a luminosity of $10^{33} cm^{-2}s^{-1}$, average current smaller than 1 A, and a perimeter of 32.7 meter. Its transverse chromaticities and second order momentum compaction are set to zero by utilizing three families of the sextupoles. The QIR dynamic aperture is calculated using a new computer code, KRAKPOT, written explicitly for small rings.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, of the U.S. Department of Energy under Contract Nos. DE-FG03-92ER40693 and DE-AC03-76SF00098.

1 Introduction

This work has been motivated by the desire to study the physics of the Φ meson and its associated decay particles, notably CP violation in the K meson system, at a luminosity level larger than 10^{33} cm^{-2} s^{-1}, or an integrated luminosity greater than 10^{40} cm^{-2} per year. Three groups, at UCLA [1], Frascati [2], and Novosibirsk [3] have proposed different designs for an electron–positron collider capable of increasing the luminosity to much larger level than has been obtained up to now in existing systems. To discuss the strategy for the difficult task of reaching a luminosity of 10^{33} cm^{-2} s^{-1}, we rewrite the luminosity ($\mathcal{L}$) in the simplified form,

$$\mathcal{L} = 10^{33}\frac{\xi}{.05}\frac{I_{(A)}E_{(GeV)}}{\beta^*_{(cm)}} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1} \ , \tag{1}$$

where ξ is the beam-beam tune shift, I the beam current in amperes, E the beam energy in GeV and β^* the ring beta function at the interaction point (IP) in cm. This expression does not include the effect of the horizontal-vertical coupling but it is accurate enough to discuss the luminosity within a factor of 2. Assuming that ξ is about the maximum ever obtained, 0.05, and that β^* has a typical value of about 3 cm, we can rewrite (1) as $\mathcal{L} = 1.5 \times 10^{32}$ cm^{-2} s^{-1} $I_{(A)}$. To obtain the design luminosity, we would then need a current of about 6 A!

An examination of $\mathcal{L}$ shows that there are three strategies possible for a high-luminosity ring, and they all imply pushing some parameter well beyond the present state of the art:

- Increase the current;
- Increase the beam-beam tune shift;
- Reduce β^*.

The Frascati project is moving in the first direction, Novosibirsk in the second, and UCLA is exploring the last one. This variety of approaches is very welcome and might put us, in the future, in a much better position to understand how to reach a large luminosity.

The Frascati design has two separate, 100 meter long, rings with up to 120 bunches per ring and a total current as large as 6A per beam. The damping time in this ring would be long, of the order of 0.1 s, when using a normal conducting magnet. To make the damping time shorter high field wiggler magnets are added to the ring [2].

The Novosibirsk project uses superconducting dipole to reduce the damping time and is based on the possibility of increasing the beam-beam tune shift by colliding round beams, another geometrical factor of two can be gained in this configuration [3].

An initial design of a QIR for the UCLA Φ factory, based on a very compact superconducting ring, was presented at the San Francisco Particle Accelerator Conference [1]. In this paper, we present a new design which has evolved from our initial work.

The UCLA approach is based on the following points;

1. A single ring.
2. Superconducting dipoles to reduce the damping time.
3. Decrease β^* and the bunch length from the centimeter to the millimeter range.
4. Use a variable momentum compaction, i.e. Quasi-Isochronous Ring (QIR), configuration to control the bunch length.

The single ring is preferred since it reduces the cost, and to date all single ring colliders have outperformed two-ring systems. Superconducting dipoles are chosen over the wiggler options to keep the ring compact, thus increasing the luminosity and reducing the cost. The small β^* and short bunch length requires less current for the same luminosity, thus simplifying the storage ring RF and vacuum systems.

The QIR [4,5,6] is our preferred option to reduce the bunch length from its present typical value in the centimeter range to the millimeter range for two reasons. Firstly, the optimum operating condition for a collider occurs when β^* is about equal to the bunch length, the shorter bunch would allow us to reduce β^* and thus increase the luminosity for a constant current. Secondly, the alternative of reducing the bunch length by increasing the RF voltage or frequency leads to complex RF systems and increases the longitudinal coupling impedance thus making instabilities more critical.

2 Quasi-Isochronous Ring

A magnetic lattice for a storage ring which can be operated as either a "normal" or QIR ring is presented here. This ring has a perimeter of 32.7 meter and is composed of two straight sections and four bending cells as shown in Fig 1. Typical ring functions are shown in Figure 2. Each cell, Fig. 3, in turn is composed of three dipoles and eight quadrupoles. In both straight sections the dispersion is zero. The tunes are 3.1 and 5.1 in x and y directions, respectively.

In our discussion of the momentum compaction α, we have to remind the reader that α is a non–linear function of the particle displacement from the ideal reference trajectory. Non–linearities become more important when we make α small. While nonlinearities will be fully taken into account in the numerical simulation. In this discussion, we consider initially only the first two terms in the expansion of α as a power series in the energy deviation while ignoring the betatron oscillation. The term α_1, the momentum compaction in the linear theory, and α_2, the first order nonlinear correction that causes a change in the synchrotron tune with energy, which is related to what we call the longitudinal chromaticity, are defined as follows;

$$\alpha_1 = \int_{RT} \frac{\eta_0}{\rho} ds, \tag{2}$$

$$\alpha_2 = \int_{RT} (\frac{1}{2}\eta_0^{'2} + \frac{\eta_1}{\rho}) ds \; . \tag{3}$$

Here η_0 is the linear dispersion function in terms of energy and η_1 describes the first nonlinear correction. Notice that the first term in the second integral, the square of the derivative of the linear dispersion, is always positive, while the second term, which can be controlled with sextupoles, can be either positive or negative, and allows us to control the value of the longitudinal chromaticity, [4,6].

In order to decrease the momentum compaction while keeping the emittance large, we have introduce a 4 degree "inverted" bend per cell at the large dispersion region and used two 47 degree "regular" rectangular bend to obtain a 90-degree bend as shown in Fig. 3.

Since the value of α_1 is controlled by the ratio of dispersion over bending radius, a small bend at high dispersion region enable us to tune α_1 to any desired value. Dispersion starts from zero in the two external superconducting dipoles, and is large at the inverted dipole, Fig. 2, therefore, a small change of the dispersion in this region can produce large change in α_1. In our case we can easily change α_1 between -0.008 and 0.005, keeping the tunes and emittance constant. A larger interval can be obtained under less restrictive conditions.

The bending dipoles are superconducting with a field of 4 T. They are rectangular magnets with field index equal to zero. The small bending radius makes these dipoles strongly focusing in the horizontal plane. To reduce the horizontal focusing and also provide vertical focusing, these dipoles have a rectangular shape with an entrance and exit angle of 23.5°. The "inverted dipole" has a field of 1 T and length of 10 cm. A list of the magnet characteristics is given in Table 1.

The β^* at the interaction point can be changed between 4 mm and many centimeters by simply altering the quadrupole gradient and relative length of drifts in the straight sections. Since near the interaction point the β function varies as $\beta = \beta^*(1 + (s/\beta^*)^2)$, The value of β function at the first quadrupole depends on its distance from the IP. In order to reduce the chromaticities generated from the first quadrupole, as β^* becomes smaller, we need to move the first quadrupole closer to the interaction point.

The chromaticities both in x and y directions and the second-order momentum compaction are set to zero with the help of three families of sextupoles located in three of the quadrupoles at the arcs. The location of these sextupoles is chosen to enforce the $-I$ principle, i.e. a phase shift of $(2n + 1)\pi$ between sextupoles, Ref [7].

The beams will be separated in the straight section and will collide only at the prescribed interaction point where the β^* has been reduced. The main characteristics of this ring are given in Tables 2 and 3. In Table 2, we give the general parameters of the ring. The other ring characteristics, like the minimum β^* at the interaction point (IP), the momentum compaction and the bunch length, will change according to the configuration that we choose.

Three examples, corresponding to different β^* at the IP are given at Table 3.

One can see the advantage of the QIR, producing a larger luminosity for less current, over the conventional solutions. The main point that we now have to discuss is the collider dynamic aperture for this ring configuration, where large nonlinear effects are expected.

3 Dynamic Aperture

The small β^*, which requires a large gradient in the final focus system, and the small bending radius, lead to larger nonlinear effects. This situation requires a more detailed and careful study than what has been used traditionally for large rings. The small bending radius in the superconducting dipoles, 0.425 m, also produces strong nonlinear effects in the particle dynamics. In order to ensure accurate results, we have developed a new code written for small rings and small bending radii. Our code , KRAKPOT, is an explicit symplectic integrator for small rings that uses the exact particle Hamiltonian, without any approximation.

Furthermore, it utilizes the full power of automatic differentiation to calculate Taylor series, from which we extract nonlinear correction to all physically relevant functions. The appendix and references [8,9,10] will provide a more detailed description of these ideas. This code is capable of 6 dimensional tracking, map calculation, full error implementation (3 rotation, 3 translation, and errors in magnetic components), and synchrotron radiation effects.

The tracking calculations have been performed three ways: 1) no sextupoles and no cavity, 2) sextupoles turned on so the chromaticities are zero in both directions, and finally 3) both sextupole and cavity on. We obtain a dynamic aperture larger than 10σ for all β^* down to the 4 mm value. Figures (4,5,6) show the result for the $\beta^* = 4$mm case. It is interesting to note that the size of dynamic aperture is limited by "nonlinear drift", i.e higher-order terms in the expansion of the Hamiltonian.

To avoid having a very large β function at the first quadrupole, thus reducing the dynamic aperture, we need to bring this element closer to the IP when we reduce β^*. This procedure has the effect of reducing the detector useful solid angle and will have implications on the detector design, that have yet to be explored.

4 Conclusion

We have shown here that it is possible to design a collider with variable momentum compaction, using an inverted bend magnet. The single particle dynamics can be made stable using 3 families of sextupoles, and one can obtain the required dynamic aperture down to a $\beta^* = 4mm$. This opens the possibility of reaching a luminosity of $10^{33} cm^{-2} s^{-1}$, with a beam current of only 1A. We notice that when β^* is reduced the first quadrupole in the interaction region focusing system must be moved closer to the interaction point. This has an effect on the useful solid angle for the detector for the Φ decays, which must be included in full discussion of Φ factories.

While our intial discussion of the momentum compaction considers only the terms α_1 and α_2, our numerical calculations include all terms in the expansion, as well as the coupling between betatron and synchrotron oscillations and a localized RF cavity.

References:

1. C. Pellegrini et al., A high luminosity superconducting mini collider for Phi meson production and particle beam physics; Proc. IEEE Part. Acc. Conf., San Francisco, p. 2856 (1991).

2. G. Vignola, DAPHNE: The Frascati PHI-factory; Proc. IEEE. Part. Acc. Conf, S.Francisco, p. 68 (1991).

3. L. M. Barkov etal, Status of the Novosibirsk PHI-factory; Proc. IEEE. Part. Acc. Conf, S.Francisco, p. 183 (1991).

4. C. Pellegrini and D. Robin, Nucl. Instr. and Meth. A301, 27 (1991).

5. C. Pellegrini and D. Robin, Electron density enhancement in a quasi isochronous storage ring; Proc. IEEE Part. Acc. Conf., San Francisco, p. 398 (1991).

6. D. Robin, E. Forest, C. Pellegrini, A. Amiry, To be published.

7. K. L. Brown and R. V. Servranckx, 11th Int. Conf. on High Energy Accelerators, CERN, Geneva, Switzerland, 1980, p.656-660

8. M. Berz, Part. Acc. **24**,109 (1989).

9. E. Forest, J. Math. Phy. **31** (5), 1133, May 1990.

10. E. Forest, M. Berz, J. Irwin, Part. Acc. **24**, 91, (1989).

Table 1

Quadrupole Strength for 4mm QIR at UCLA

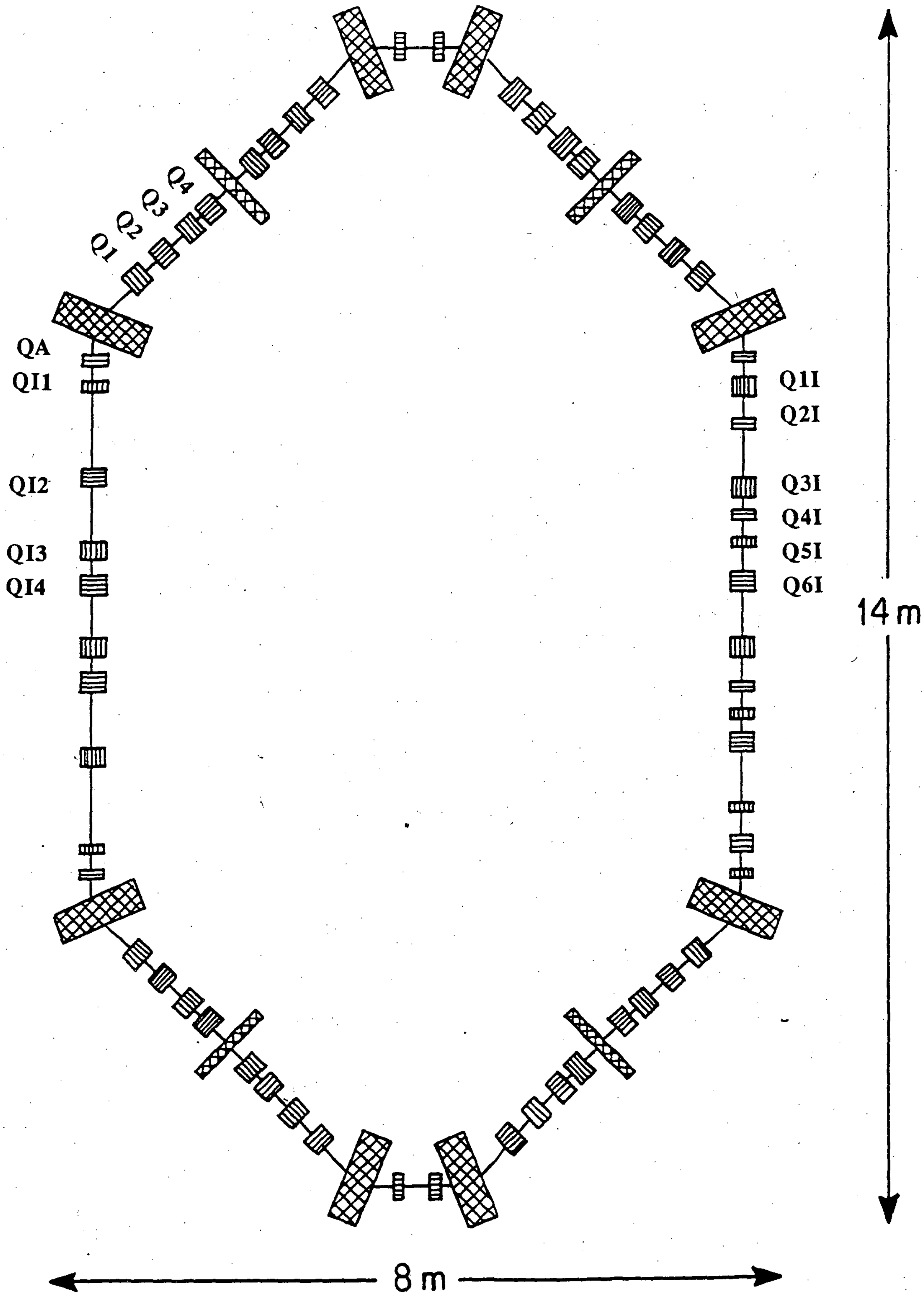
	Length(m)			
NAME		K1 (1/m^2)		K2 (1/m^3)
	0.2			
QI4		-34.26		
	0.2			
QI3		16.41		
	0.2			
QI2		-5.81		
	0.1			
QI1		4.43		
	0.1			
QA		-0.065		
	0.2			
Q1		5.5		50.32
	0.2			
Q2		-9.16		-84.23
	0.2			
Q3		9.85		
	0.2			
Q4		-4		26.14
	0.2			
Q1I		6.85		
	0.1			
Q2I		-24.39		
	0.2			
Q3I		-1.03		
	0.1			
Q4I		22.41		
	0.1			
Q5I		-24.65		
	0.2			
Q6I		-1.93		

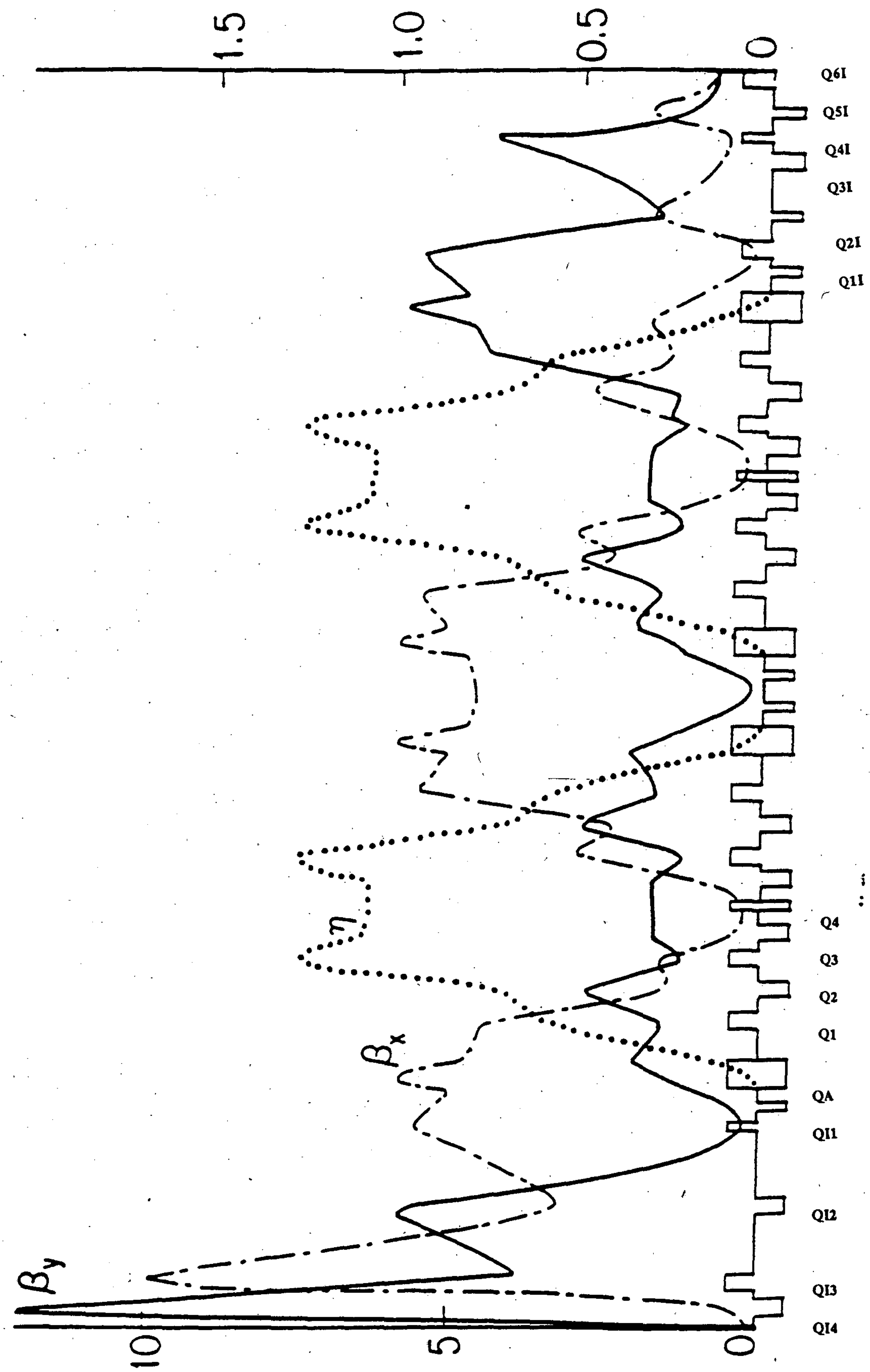
Table 2		
QIR Parameter List		
Energy , Mev		510
Circumference, m		32.7
Horizontal Tune		3.1
Vertical Tune		5.1
Energy Loss/ Turn		14.9
Damping Time, Horizontal, ms		7
Damping Time, Vertical, ms		7.5
Emittance, mm mrad		1.03
RF Frequency, MHz		499
RF Voltage, KV		100

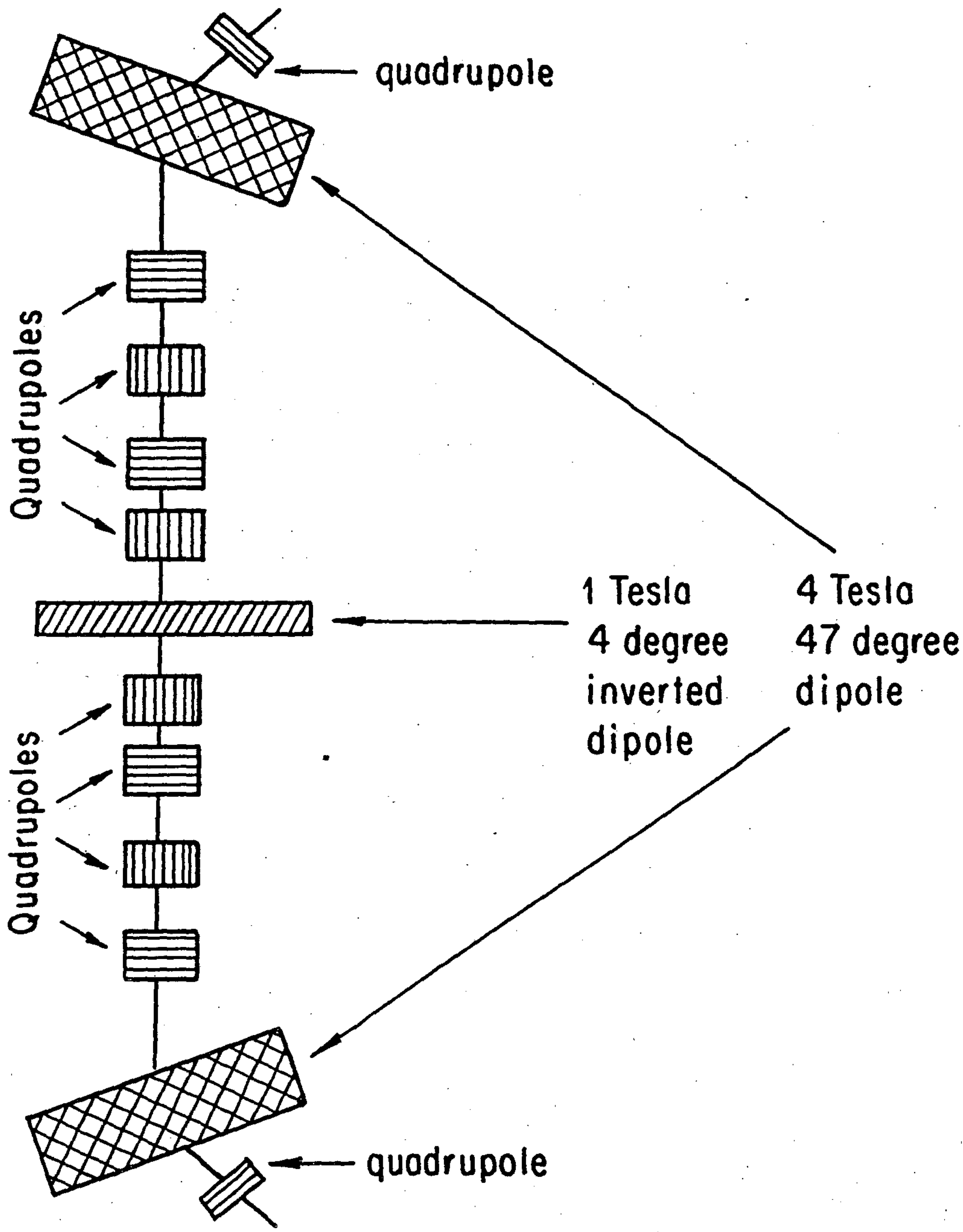
	Table 3					
Comparison between three possible QIR rings.						
Beta vertical at IP, cm				1.2	0.8	0.4
Beta horizontal at IP, cm				20	23	18
Distance to first quad, cm				25	15	15
Particles/ Bunch 10 ^11				1.47	1.22	1.33
Luminosity/bunch, 10^32 cm ^-2 s^-1				1.035	1.28	2.67
Number of bunches				6	6	6
Average current/ bunch, mA				217	179	196
Total Luminosity, 10 ^32 cm^-2 s^ -1				6.21	7.68	16.02
	-0.005	< Alpha 1 <	0.008			

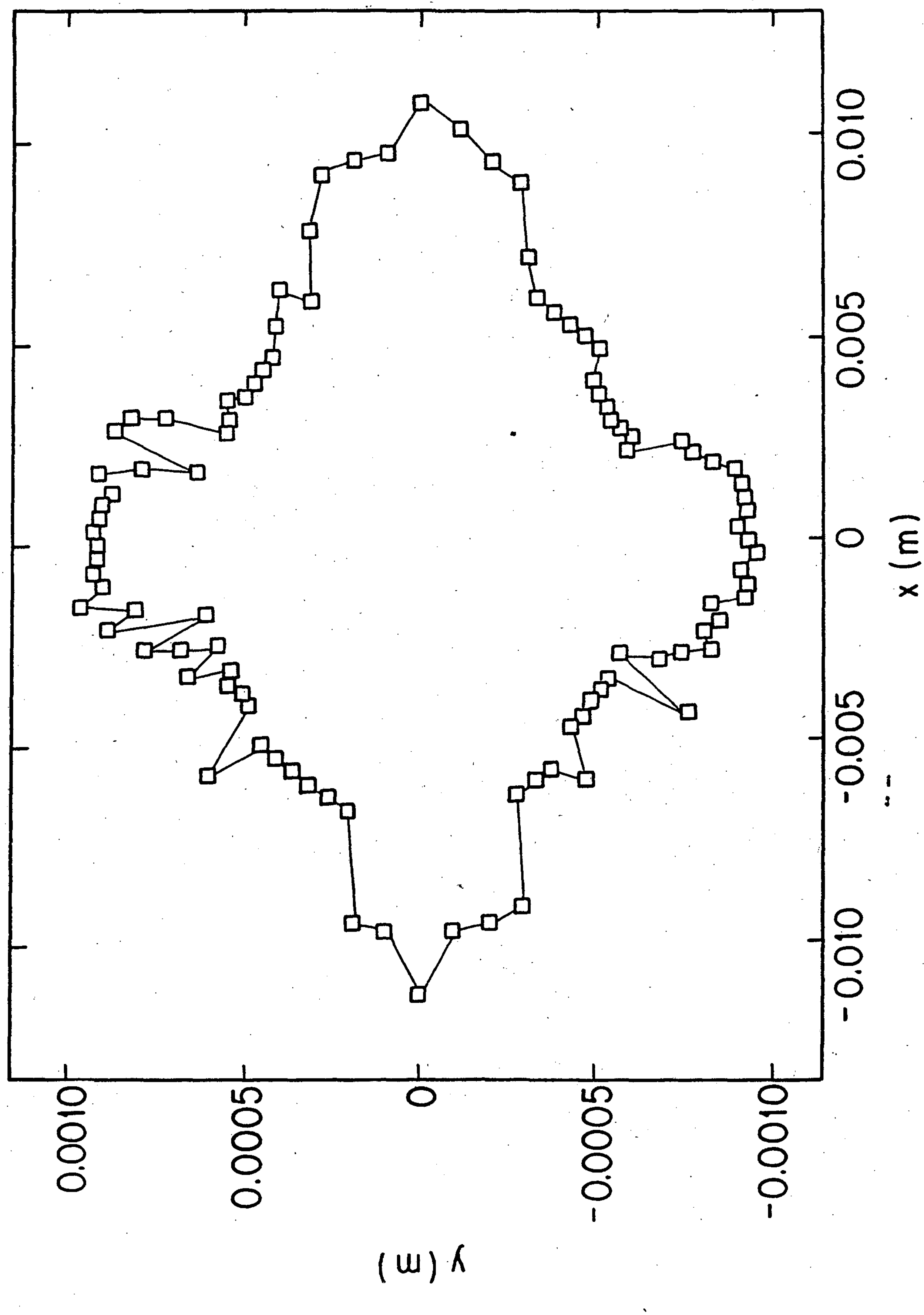
FIGURE CAPTIONS:

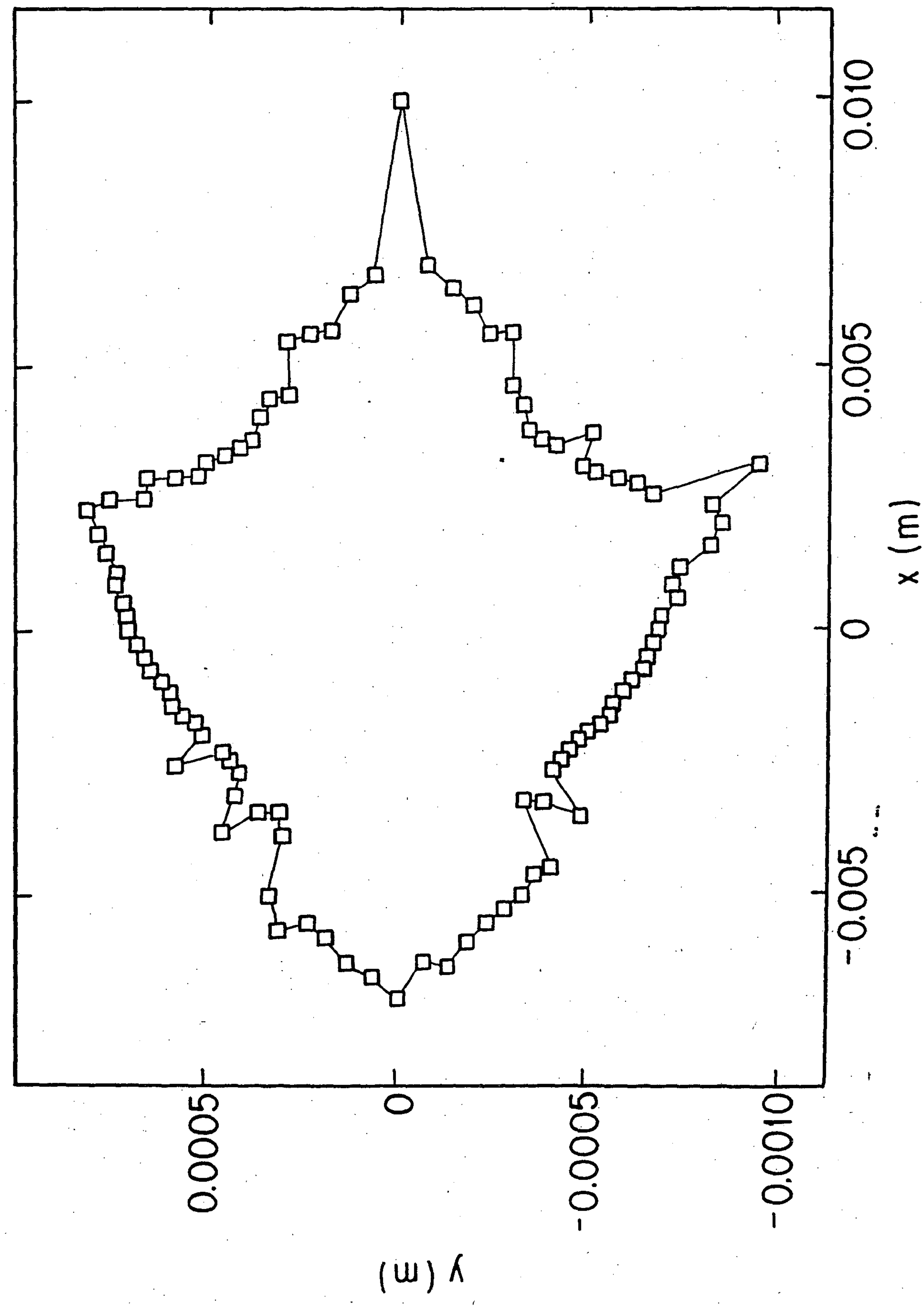
- Figure 1– Layout of the QIR.
- Figure 2– β and η functions for the 4 mm ring.
- Figure 3– Drawing of a 90 degree bend.
- Figure 4– Dynamic aperture in X-Y plan for the 4 mm ring. $10\sigma_x = .0042$ and $10\sigma_y = .00065$, No sextupole or cavity.
- Figure 5– Dynamic aperture in X-Y plan for the 4 mm ring. No cavity, $10\sigma_x = .0042$ and $10\sigma_y = .00065$.
- Figure 6– Dynamic aperture in X-Y plan for the 4 mm ring. With cavity, sextupoles, and $\delta = \pm 0.01$, $10\sigma_x = .0042$ and $10\sigma_y = .00065$.


Q1
Q2
Q3
Q4
QA
QI1
QI2
QI3
QI4
Q1I
Q2I
Q3I
Q4I
Q5I
Q6I
14 m
8 m

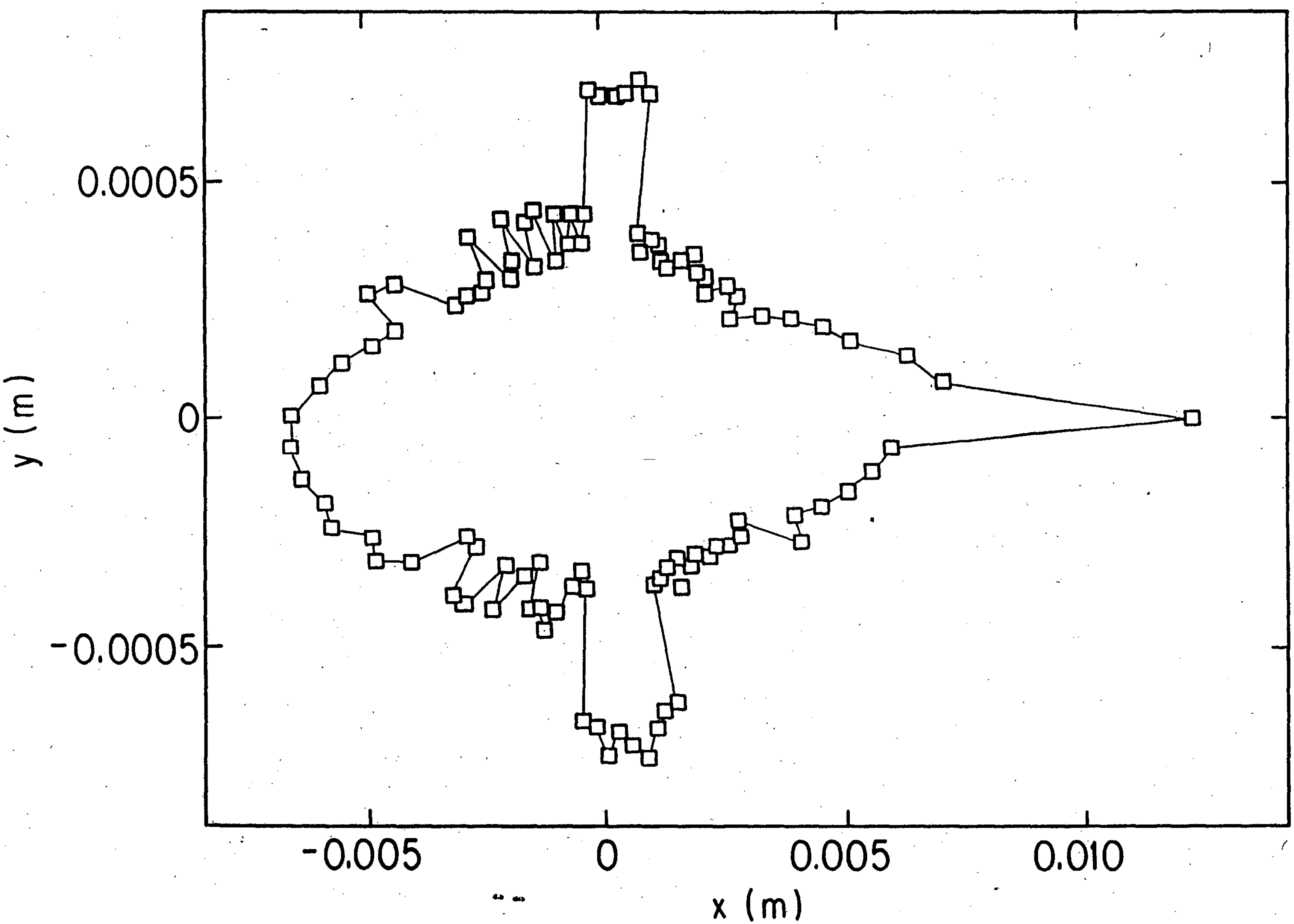

1.5
1.0
0.5
0
10
5
0
β_y
β_x
η
Q6I
Q5I
Q4I
Q3I
Q2I
Q1I
Q4
Q3
Q2
Q1
QA
QI1
QI2
QI3
QI4


quadrupole
Quadrupoles
1 Tesla
4 degree
inverted
dipole
4 Tesla
47 degree
dipole
Quadrupoles
quadrupole


x (m)
y (m)
-0.010
-0.005
0
0.005
0.010
0.0010
0.0005
0
-0.0005
-0.0010



x (m)
y (m)
-0.005
0
0.005
0.010
0.0005
0
-0.0005
-0.0010


0.0005
0
-0.0005
y (m)
-0.005
0
0.005
0.010
x (m)

Appendix A: Why we use an "exact" integrated package for simulation

We will first address the issue of model exactness. Why is that certain standard approximations in the model itself (i.e. Hamiltonian) breaks down?

The computation of transfer maps (i.e. tracking or Taylor series) in small machines requires special attentions to the details and geometry of individual magnets. Through the years, accelerator physicists have used simplistic models for the simulation of circular rings. In these models, ideal quadrupoles and ideal bends are linear in the transverse variables. Fringe fields are totally absent except for vertical focusing in bends. These approximations can break down as rings get smaller and their focussing gets stronger. In particular, in a small Φ Factory, strong nonlinear effect can be generated in the interaction regions by a system of drifts and ideal quadrupoles. This is quite obvious if we just look at the Hamiltonian:

$$H = -p_z = -[(1+\delta)^2 - p_x^2 - p_y^2]^{1/2} - \delta + (1/2)K(z)(x^2 - y^2) \tag{1}$$

If we expand H we obtain;

$$H = \frac{p_x^2 + p_y^2}{2(1+\delta)} + (1/2)K(z)(x^2 - y^2) + \frac{(p_x^2 + p_y^2)^2}{8(1+\delta)^3} + \ldots \tag{2}$$

The first two terms in equation (2) are the ingredients of the usual kick codes used in large machine simulations. The next term is a nonlinearity which is like a uniformly distributed octupole. Clearly, to see its effect, we should rewrite H in Floquet variables. Here it is convenient to use the "anti" Courant-Snyder transformation using one of the Twiss parameters α, β, γ, as

$$x_f = \frac{1}{\sqrt{\gamma_x}} x_i - \frac{\alpha}{\sqrt{\gamma_x}} p_i \tag{3}$$

$$p_f = \sqrt{\gamma_x} p_i \tag{4}$$

and similarly for the y direction. Then, it is possible to show that for $\delta = 0$, H becomes;

$$H = \frac{K(z)(x_i^2 + p_{xi}^2)}{2\gamma_x} + \frac{K(z)(y_i^2 + p_{yi}^2)}{2\gamma_y} + \frac{(\gamma_x p_{xi}^2 + \gamma_y p_{yi}^2)^2}{8} \tag{5}$$

In equation (5), the linear phase advance is different from the Courant-Snyder choice. Indeed the transformation has been tailored to a momentum dependent nonlinearity. The important part is the third term; it contributes in the lowest order to the $4\nu_x, 2\nu_y \pm 2\nu_x, 4\nu_y$ resonances, the nonlinear $2\nu_y$ and $2\nu_x$ resonances as well as producing tune shifts with amplitude. This becomes dangerous whenever the Twiss parameter γ's are large which is precisely the case in the small interaction region. This is a fundamental limitation on the design of small Φ factories.

Another issue is the importance of the quadrupole fringe field. To first order in the mid-magnet gradient k_0, it is possible to derive an expression for the motion through the fringe field. Again this is an "octupole like" nonlinearity. The expression was first derived by Lee-Whiting;

$$\Delta x = \pm(\frac{1}{12}x^3 + \frac{1}{4}xy^2)k_0 \tag{6}$$

$$\Delta x' = \pm(\frac{1}{2}xyy' - \frac{1}{4}x'(x^2 + y^2))k_0 \tag{7}$$

$$\Delta y = \pm(\frac{1}{12}y^3 + \frac{1}{4}yx^2)k_0 \tag{8}$$

$$\Delta y' = \pm(\frac{1}{12}xyx' - \frac{1}{4}y'(x^2 + y^2))k_0 \tag{9}$$

The plus sign refers to the entrance and the minus sign to the exit of the quadrupoles. This makes an analytical "back-of-the-envelop" estimate of this effect rather hard because in a weakly focussing systems they would tend to cancel. Hence it is best to have this fringe field as a switch which one can turn on and off. In some ring, such as Aladdin, the tune shifts with amplitude produced by this quadrupole effect were large compare with chromatic sextupoles. It should be noted that unlike higher multipole fringe fields, the quadrupole end field provides a qualitatively different effect (i.e making the system nonlinear). For this reason, it is important to equip a simulation code with a quadrupole "switch".

This summarizes the issue of model exactness. Of course, the discussion can be extended to bends which, when approximated, produce a different chromaticity. Basically, we are saying to the designer to use a correct Hamiltonian and approximate only after careful checks.

Once the appropriate Hamiltonian has been introduce in a simulation code (symplectic integrator if possible, otherwise a high order integrator),we need to be able to perform some calculations. In the case of a Quasi-Isochronous machine, we may want to compute the path length as a function of δ. We may want to compute the equilibrium emittances, the tune shifts with amplitude etc...

It is our belief, confirmed by personal experience that perturbative calculations should be done in a way absolutely self-consistent with the simulation code.

For example, in a QIR ring, it is dangerous to compute the beam length σ_L using some "canned" formulae which do not take into account the change of the linear momentum compaction resulting from an energy loss of a particle during the radiation process. This problem can be avoided if a code is equipped with the ability to radiate so that the new synchronous orbit can be found. This truly mimics the actual ring.

In summary, the codes we use are fully 6-D and can radiate energy. All analytical calculation are done with an automatic differentiation package such as the old Differential Algebra package of Berz, insuring the self-consistency. Then the analysis is performed with a sub-library of this differentiation package which handle map and their various Lie representations. All results are then checked by tracking if necessary. Anything less can be very dangerous; designer beware!

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720