

## COMPARISON OF ACCELERATOR CODES FOR A RHIC LATTICE\*

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### Abstract

We present the results of comparisons of performances of several tracking or/and analysis codes. The basic purpose of this program was to assess reliability and accuracy of these codes, i.e. to determine the so-called "error bars" for the predicted values of tunes and other lattice functions with a minimum and, if possible, to discover potential difficulties with underlying physical models in these codes, inadequate algorithms, residual bugs and the like. Not only we have been able to determine the error bars, which for instance for the tunes at  $dp/p = +1\%$  are  $\Delta v_x = 0.0027$ ,  $\Delta v_y = 0.0010$ , but also our program has brought about improvements of several codes.

### Introduction

The importance of computer programs in accelerator physics, cannot be overemphasized. Their predictions have proved to be an invaluable guide during the process of lattice designing, and during the subsequent processes of better understanding, improving and upgrading of an accelerator. However, such computer programs are characterized by a variety of serious limitations. First and foremost, these programs do not handle computation and analysis on an accelerator; rather they do all this on a model of an accelerator. Therefore, they are limited by the validity of models that contemporary accelerator theory can offer to account for what has been observed in practice. A good example of a model limitation is treating of fringe field effects for the bend, in the so-called hard-edge approximation. Second and almost equally important, these programs are not capable of handling even the accepted models exactly. In particle tracking, for instance, generally the most accurate approach would be to take the exact equations of motion, dictated by the adopted physical model, and integrate them numerically through the lattice. Then the better numerical integration methods and the better computer used, the closer the results would be to the exact. However, barring some very special cases, this is completely ruled out by computational demands imposed on a computer. Consequently, one has to resort to various approximations. Given the array of codes on the market, and given the fact that there are hardly such notions as the "best model" or the "best approximation," it is expected that by using different codes one gets different numerical predictions for the same physical quantity. So for each computed quantity, the results will vary over a certain range of values. Knowledge of these ranges, for a specific accelerator, is a valuable guide to the user in his judgement as to how much confidence to place in the results of a particular run with a particular code on that lattice. Such knowledge can be acquired only by running several codes with the same lattice input conditions and by comparing the results. With this in mind, we proceeded with the program we describe in this note.

### Codes Subject to Comparisons

We have compared several codes which are available at BNL. In an alphabetic order they are: FASTRAC,<sup>1</sup> MAD,<sup>2</sup> ORBIT,<sup>3</sup> PATRICIA,<sup>4</sup> PATRIS,<sup>5</sup> SYNCH<sup>6</sup> and TEAPOT.<sup>7</sup> Three different computer systems were used to run these codes. FASTRAC, PATRICIA, PATRIS and TEAPOT were run on the CRAY X-MP, ORBIT and SYNCH on the CDC which is not in operation any more, while both versions of MAD were run on the VAX.

### Choice of Lattice for Comparison

Although one could have contemplated creating special kinds of inputs for the purpose of code testing, this would not have been a very productive approach. The primary purpose of the whole program was not code development and safeguarding them against any contingency one could envision; the purpose was to test how these codes work in the environment they have been, are being, and will be used, i.e. how well they fare on the lattices they are supposed to handle. Therefore the natural choice was to run these codes on a RHIC lattice,<sup>8</sup> which is sufficiently "coarse" to cause even slightly different algorithms and procedures employed by these codes to display noticeable differences.

The RHIC lattice we used was the currently considered lattice at the outset of this program. It was later abandoned in favor of another lattice, with sector bends instead of rectangular ones, but we adhered to the original lattice which was better for the purpose of testing, even though it turned obsolete in the midst of our program implementation.

### What the Codes Supply and What Was Compared

The codes we have tested are able to perform a wide variety of calculations. Using one or more of these codes, one can for instance track particles without or with synchrotron oscillations, perform a closed orbit analysis, obtain a Lie algebraic representation of the transfer map, perform linear optics calculation, (re)design a lattice and many other things. However, by and large these capabilities are not shared among all of these codes. To test them, it would mean comparing selected subgroups of these codes, with specific groups being formed according to specific shared capabilities. Time limitations have, of course, prevented us from testing everything. Therefore, we have selected a computational feature common to all of these codes. That was calculation of various lattice functions, such as for instance tunes, closed orbit, beta functions at various locations, and momentum dispersion and/or closed orbit function at the same locations as beta functions. The locations were the following three points of interest: the middle of an inner arc, the first following in-to-out crossing point and the next crossing point which was out-to-in. In the subsequent text, these three points will be named SYM, CRIO and CROI, respectively.

We should mention that most codes evaluate transfer matrices with respect to the commonly used noncanonical coordinates  $(X, X', Y, Y')$ . FASTRAC and (presumably) MAD, on the other hand, evaluate the transfer matrix with respect to the canonical coordinates  $(X, P_x, Y, P_y)$ . Therefore, their  $\beta$ -functions have to be divided by  $(1 + \delta)$  to conform to the accepted standards. This important fact, however, is not mentioned in the code manuals.

### Some Specific Problems Revealed by Comparisons

As mentioned, the primary goal of this program was not to hunt specifically for problems and bugs, but to determine the ranges of predictions for each computed quantity instead. However, a possibility of discovering some problems was realistically admitted, even though we had had some advanced knowledge of only one problem, that of PATRICIA's deficient closed orbit finder, to be specific. In the course of testing, all of the codes we compared exposed one weakness or another. We will explain the known causes of these weaknesses in the next section. Here we mention them in an alphabetic order.

FASTRAC revealed a bug in its edge focusing routine. Our attention to this bug was accidentally drawn by the observed (unrelated) discrepancy between the total length of the machine computed by the code and the actual length of the machine. Had the

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code supplied a correct length of the machine, the bug would not have shown up at all on a machine as big as the RHIC.

MAD revealed a discrepancy in predicting tune dependence with momentum deviation  $\delta$ , when compared with the rest of the codes we tested. The difference between MAD's prediction and that of any other code is manifestly quadratic in  $\delta$ , in both planes. On the other hand, the much smaller differences among other codes are all linear in  $\delta$ . Both versions of MAD, i.e. 4.03 and 6.01, displayed the same tune versus momentum deviation behavior. The origin of the discrepancy is still not known.

ORBIT displayed a discrepancy in predicting tune values even for on-momentum, i.e.  $\delta = 0$  values, in both planes. However, for off-momentum values the residual discrepancy is linear in  $\delta$ , once the on-momentum discrepancy is subtracted out. The error was corrected by the fact that at the time the code would not handle correctly the entrance and exit angles.

PATRICIA did not reveal any further serious difficulties, aside from its old problem with the closed orbit finder. The problem was subsequently removed by adding the subroutine taken from PATRIS for the closed orbit finder based on the Newton's method.

PATRIS initially displayed a big discrepancy in predicting the tune dependence on momentum deviation. Like MAD's discrepancy, this one was also quadratic in  $\delta$ , in both planes. But unlike the MAD case this one was quickly understood and corrected. The source of the errors was the wrong assumed dependence with momentum of the focussing elements. The corrective measure was to take PATRIS in line with codes like FASTRAC and TEAPOT.

SYNCH strictly speaking did not display problems during this set of comparisons, with the exception of small discrepancies in the momentum dispersion when compared to the other codes. We believe now that the discrepancy is due to a curious way of handling the off momentum dependence of the motion in a quadrupole which we understand still remains unmodified.

TEAPOT did not display much trouble during these tests, except that we were quickly halted in our attempt to split the bend into more than 6 thin lenses. Beyond 6 the code crashed due to underflow/overflow condition.

#### Reliability of Code Predictions. Error Bars after the Implementation of Corrective Measures

As already mentioned, there are two kinds of quantities we compared. First group is composed of the so-called global characteristics of the machine, such as for instance on-momentum tunes, transition gamma, on-momentum path length over the ring, bare and corrected chromaticities, etc. We present these general characteristics in Table 1. Some of them, like on-momentum tunes, tell us about the ability of the code to make realistic predictions, in addition to serving as code and/or lattice debugging tools. Unfortunately, not all the codes supplied all these quantities, thus many places in the table remain filled with asterisks. For the available quantities, we notice excellent agreements, with the exception of ORBIT's on-momentum tunes, whose deviation from the other codes' predictions is, however, well understood.<sup>3</sup>

Second group of items that we have compared consists of various quantities whose momentum dependence is being evaluated and compared. With the exception of tunes, whose momentum dependence we include in this group, all the quantities are local, i.e. they explicitly depend on the location in the lattice where they are being observed. As mentioned in introductory chapters, we have selected three locations. Note that ORBIT and PATRICIA did not supply the momentum dispersion function, nor had PATRIS been doing it until we accommodated an extra algorithm for that purpose.

First we present the error bars in Table 2. They are given in absolute quantities for  $\delta = -1\%$  and  $\delta = +1\%$ , and are evaluated as  $|Q_{\max} - Q_{\min}|$  for the particular quantity  $Q$ . They refer to the results obtained after the corrective measures had been taken. There are two important exceptions to this rule. The first one refers to ORBIT's tune dependence on momentum deviation. The second one refers to the same quantities produced by MAD, which were

simply dismissed from the tune error bar determination, being considerably off. The variation of the betatron tune versus momentum is shown in Figs. 1 and 2. It is seen that the results from MAD deviate considerably from those of the other codes which differ at most by 0.002 at  $\delta = 1\%$ . Once corrective measures were taken to remove bugs, inconsistency and plain errors, all the codes agreed with each other for the behaviour of the  $\beta$ -functions versus momentum. We found nevertheless a curious discrepancy between SYNCH and the other codes on the results of the dispersion function as shown in Fig. 3. We believe we understand the source of this discrepancy as we have explained above.

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Table 1. Some General On-Momentum Lattice Characteristics

Quantity	SYNCH	PATRIS	PATRICIA	FASTRAC	MAD	TEAPOT	ORBIT
2*PI*B	3833.8677	3833.8677	3833.8677	3833.868	3833.8677	****	****
GAMMA	25.44196	25.44196	25.43872	****	25.441958	****	****
Qh	28.82850	28.82850	28.82850	28.82850	28.82850	28.82850	28.82850
Qv	28.82903	28.82903	28.82903	28.82903	28.82904	****	28.82910
Cx bare	-56.39246	-56.605	-56.532	-56.5355	****	-56.3911	****
Cy bare	-56.39131	-56.344	-56.464	-56.4724	****	-56.4058	****
Cx sext	0.09193	0.120	-0.068	-0.05106	0.093425	0.09401	****
Cy sext	0.05025	0.097	-0.022	-0.03094	0.046681	0.0365	****
Bth(SYM)	50.2645	50.26448	50.2645	50.2645	50.264	****	50.08
Btv(SYM)	8.4948	8.49482	8.4948	8.4948	8.495	****	8.48
ETA(SYM)	1.5010	1.50100	1.50100	1.50101	1.501	****	1.501
Bth(CRIO)	3.1314	3.13145	3.1314	3.1314	3.131	****	3.14
Btv(CRIO)	3.1331	3.13312	3.1331	3.1331	3.133	****	3.13
ETA(CRIO)	0.0079	0.00786	0.00786	0.00786	0.008	****	****
Bth(CROI)	3.1314	3.13145	3.1314	3.1314	3.131	****	3.14
Btv(CROI)	3.1329	3.13292	3.1329	3.1329	3.133	****	3.13
ETA(CROI)	0.0091	0.00912	0.00912	0.00912	0.009	****	****

Table 2. Errors at Momentum Deviation -1% and +1%

Quantity	$\delta p/p = -1\%$			$\delta p/p = +1\%$		
	Average value	Absolute error	Error in per cent	Average value	Absolute error	Error in per cent
Qh	.825637	.002855	.346	.835174	.002735	.327
Qv	.827225	.000707	.085	.832623	.001010	.121
XCS(m)	1.48340	.00100	.067	1.48698	.00114	.076
ETA(SYM)	1.45834	.01150	.789	1.47771	.01369	.926
ETA(CRIO)	0.02073	.00190	9.165	0.00179	.00197	110.056
ETA(CROI)	0.01858	.00170	9.150	0.00712	.00188	26.404
Bth(SYM)	26.70090	.10870	.407	90.71510	1.35690	1.496
Btv(SYM)	9.45225	.03233	.342	7.11785	.07830	1.100
Bth(CRIO)	3.99329	.01160	.290	3.10780	.01440	.463
Btv(CRIO)	3.81953	.00696	.182	3.13665	.01410	.450
Bth(CROI)	3.95614	.01400	.354	3.28574	.01150	.350
Btv(CROI)	3.76993	.00570	.151	3.35948	.00780	.232

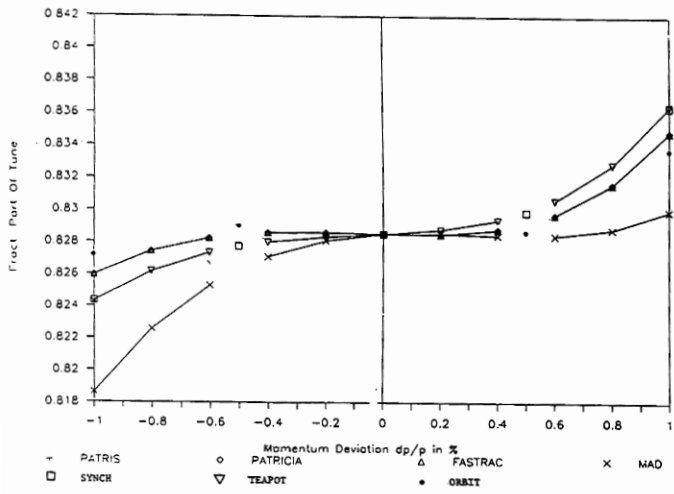


Fig. 1. Tune Dependence on Momentum-Horizontal Plane.

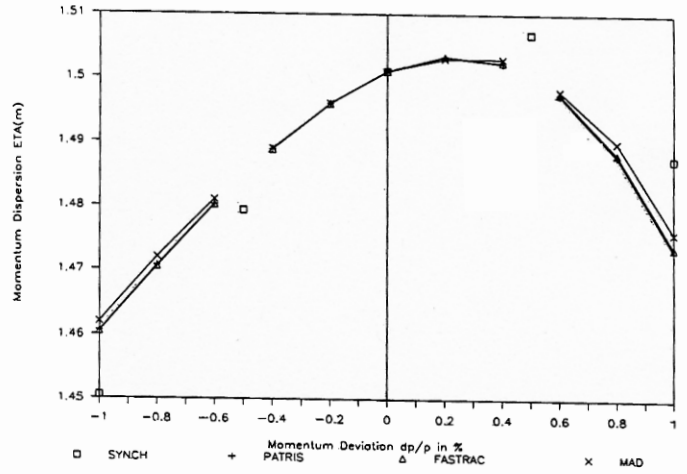


Fig. 3. Dispersion Dependence on Momentum (middle of the arc).

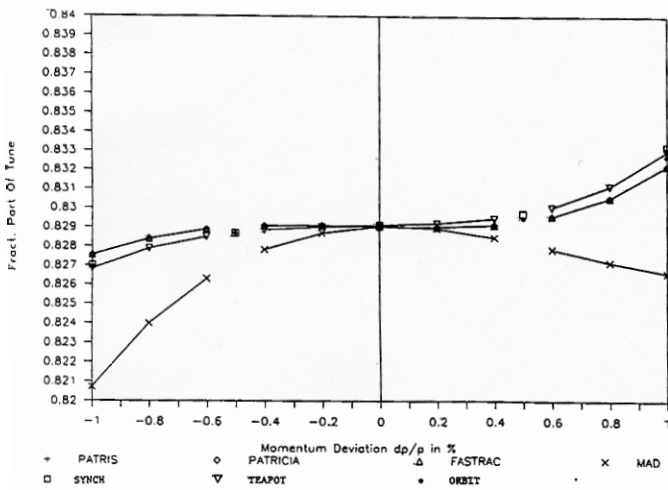


Fig. 2. Tune Dependence on Momentum-Vertical Plane.