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A TOOL FOR SYMMETRY STUDIES IN CIRCULAR MACHINES *.

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ABSTRACT

The use of the C [mrad/Amp] conversion factors of the orbit corrector magnets in the study of the symmetry properties of a circular accelerator or storage ring, and in the determination of the ratios of the β -functions at corrector locations is discussed. Measurements obtained for the VUV and X-ray rings of the NSLS at Brookhaven National Laboratory are presented.

INTRODUCTION

The mathematical model of an accelerator can be used to both control its operation and to simulate its behaviour. Part of the model is the conversion between the computer controlled excitation currents and the actual fields acting on an average particle in the magnet. This can be described by a constant C [field/current] conversion factor in the region where the field changes linearly with the current. In the "nonlinear" region one can approximate the field as a polynomial function of the current, in which case a set of polynomial coefficients describe the conversion.

Measurement of these conversion factors may be used to study the symmetry properties of circular accelerators and storage rings, and to deduce the β -function ratios at the orbit corrector magnets.

This analysis, in conjunction with other measurements, can yield a complete model of a circular machine or storage ring. Other measurements include beam-size, tune and chromaticity changes as a result of varying the strengths of each quadrupole and sextupole around the ring, etc.

METHOD

Conversion factors can be obtained [refs.1-3] by comparing measured and model-calculated physical quantities (e.g. v , η , ξ , etc.). This way of calculating the conversion factors calibrates the model and the magnet together, effects not explicitly

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accounted for in the model, are included in the conversion factors ⁺.

The $C_j = (\frac{\Delta\theta}{\Delta I})_j$ [mrad/Amp] conversion factor of the j-th corrector in the ring is calculated [ref.3] by comparing the measured $\Delta\bar{x}^{meas}$ difference orbits due to a ΔI [Amp] current change, with the corresponding $\Delta\bar{x}^{calc}$ orbit derived from model calculations with $\Delta\theta$ [mrad] kick. The orbit change at the i-th PUE due to a kick on the j-th corrector is calculated as:

$$\Delta x_i^{calc} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin(\pi \nu)} \cos(\pi \nu - |\Delta \phi_{ij}|) \Delta \theta_j$$

the effect of a corrector is determined by its strength ($B \cdot l$) and position (β) in the ring. identical correctors in identical positions in identical superperiods have the same C conversion factors. In general, if the j-th and k-th correctors are identical, the ratio of the corresponding conversion factors are proportional to the square root of the ratio of the corresponding β 's: $C_j/C_k \approx \sqrt{\beta_j/\beta_k}$. Thus, measurement of the conversion factors yields information on the ratios of the β 's at the correctors as well as on the symmetry properties of the ring.

MEASUREMENT

The actual measurement of the C conversion factors is time consuming and though trivial, it requires concentration and many "actions" at the operator terminal.

The minimum number of orbits which must be measured is equal to the number of correctors (H & V) in the ring. This number can double if reference orbits are not stable within 50μ and must therefore be measured for each new "kicked" orbit. It is especially time consuming when one wants to check the measured orbits in order to remeasure them immediately if certain criteria are not met. In addition, it is advisable to check that the correctors are actually following the desired setpoint changes.

As a result of these considerations, the procedure for measurement of the C 's was "automated" [ref.4]. A supervisor program, which activates the necessary programs (MEASURE orbit, COMPARE orbits, READ & SET correctors) according to a predetermined logic was developed. Operator intervention during this procedure is minimal.

⁺ If the model were perfect, then the conversion factor of a corrector magnet would be equal to the kick due to the integrated field, $\int B dl$, "bench-measured" with 1 Amp excitation current.

RESULTS and DISCUSSION

In the VUV ring, there are 4 horizontal and 4 vertical correctors in each superperiod. There are 4 superperiods in the ring with two undulators (FEL and TOK) in the straight sections between SP-1 & 2 and SP-3 & 4, respectively. The undulators are "compensated" so that their effect is restricted to the immediate neighborhood of the undulators. In both planes, there are 2 *groups* of correctors which are identical (within tolerance) and are in reflex symmetrical positions in the superperiods. Correctors #1 and #4 belong to one group, correctors #2 and #3 belong to the other. The β_x , β_y and η_x machine functions plotted over half the (reflex symmetrical) ring and the location of the correctors are shown on Fig.1.

Calibration measurements were performed under three different conditions:

1. at 745 Mev with the FEL undulator closed and the TOK undulator open,
2. at 745 Mev with the FEL undulator open and the TOK undulator closed,
3. at 400 Mev with the FEL undulator open and the TOK undulator closed,

Figs. 2-4 show the conversion factors for the above three conditions. Data, corresponding to correctors #1, #2, #3 and #4 are marked by $\square$, $\circ$, Δ and ∇ . In addition to the individual data, the conversion factor averaged for the m -th correctors in all superperiods is also shown on the figures.

The $\bar{C} \pm \delta\bar{C}$ average and the σ standard deviation are presented in Table-1 for the two groups of correctors. They are calculated as:

$$\bar{C} = \frac{\sum C_j \cdot w_j}{\sum w_j}, \quad \delta\bar{C} = 1/\sqrt{\sum w_j} \quad \text{where } w_j = \frac{1}{\delta C_j^2}$$

$$\sigma = \sqrt{\frac{\sum (C - \bar{C})_j^2}{N-1}}$$

The $\dot{C} = \frac{dC}{ds} (= \frac{C}{2\beta} \dot{\beta})$ derivative at the end-points and at the mid-point (reflex symmetry) of the superperiods are approximated by $\frac{\Delta C \pm \delta(\Delta C)}{\Delta s}$, where the difference is taken between the (symmetrically positioned) two correctors around the end- and mid-points. That is, Δs_{end} is calculated between the 1-st correctors in each superperiod and the 4-th correctors in the preceeding superperiods, and Δs_{refl} is calculated between the 2-nd and 3-rd correctors in each superperiod. Correspondingly, for the i -th superperiod:

$$\Delta C_{end}^i = C_4^{i+1} - C_1^i, \quad \delta(\Delta C_{end}^i) = \sqrt{(\delta C_4^{i+1})^2 + (\delta C_1^i)^2}$$

$$\Delta C_{refl}^i = C_3^i - C_2^i, \quad \delta(\Delta C_{refl}^i) = \sqrt{(\delta C_3^i)^2 + (\delta C_2^i)^2}.$$

The weighted average over the four superperiods at the end or at the reflex points, $\overline{\Delta C} \pm \delta(\overline{\Delta C})$, is then used to estimate $\bar{C}_{end}$ and $\bar{C}_{refl}$, which are also given in Table-1.

If the superperiods were truly reflex-symmetric and identical, one would expect the σ standard deviation to be less than or comparable to $\delta\bar{C}$, and β to be 0.

Table-1

	745 Mev				400 Mev	
	FEL closed TOK open		FEL open TOK closed			
	j=1,4 end	j=2,3 refl	j=1,4 end	j=2,3 refl	j=1,4 end	j=2,3 refl
H $\bar{C}$	.79±.02	.60±.02	.81±.02	.64±.02	1.50±.04	2.54±.05
O σ	±.03	±.02	±.06	±.02	±.06	±.19
R $\bar{C}$	.00±.01	.00±.01	.01±.01	.00±.01	.01±.03	.01±.03
V $\bar{C}$	.84±.02	.47±.01	.97±.02	.54±.01	1.94±.04	1.09±.03
E σ	±.07	±.03	±.06	±.04	±.30	±.14
R $\bar{C}$	.01±.02	.01±.02	.01±.01	.01±.01	.04±.02	.07±.02

Table-1 shows that at 745 Mev there is no asymmetry to speak of horizontally; $\sigma \approx \delta\bar{C}$ (except for the group-1 correctors in the second case, where $\sigma \approx 3 \cdot \delta\bar{C}$), and $C \approx 0$. Vertically however, the spread in the data is more significant; $\sigma \approx 3 \cdot \delta\bar{C}$.

At 400 Mev there is a large spread in the data in both planes; $\sigma \geq 3 \cdot \delta\bar{C}$ for all cases and groups of correctors. In addition, vertically $\bar{C} = .04 \pm .02$ and $.07 \pm .02$ at the end and mid-point respectively. Assuming $\beta_y = 8$ and 4.5 m at the location of the group-1 and group-2 correctors (as model calculations indicate), these values correspond to $\beta = 1.1$ and 2.2.

Table-2 contains the group-averaged horizontal and vertical conversion factors of the correctors for each of the three conditions. The ratios of C_{400} / C_{745} in the FEL open TOK closed cases are also given for each group.

Table-2

	745 Mev		400 Mev	
	FEL closed TOK open	FEL open TOK closed		$\left(\frac{C_{400}}{C_{745}}\right)_{TOK\ cl}^{FEL\ op}$
$C_x^{1,4}$	0.795	0.81	1.51	1.86
$C_x^{2,3}$	0.60	0.645	2.54	3.94
$C_y^{1,4}$	0.83	0.98	1.93	1.97
$C_y^{2,3}$	0.46	0.535	1.11	2.07

The difference in the conversion factors of the same group of correctors in the first two cases (at 745 Mev) is indicative of the slightly different β 's.

For linear devices, the conversion factors should scale inversely with the energy, i.e. $C_{400} / C_{745} = 1.86$. Comparing the FEL open/TOK closed cases at 745 and 400 Mev, the ratios of the conversion factors are in good agreement with the expected value for linear devices except $C_x^{2,3}$ which corresponds to backlegwindings.

In the X-ray ring, there are 5 horizontal and 5 vertical correctors in each of the 8 superperiods. In both planes, the #1 and #5 correctors (group-1) and the #2 and #4 correctors (group-2) are identical within tolerance and are in reflex symmetrical positions in each superperiod. The third group of correctors consists only of the #3 correctors in each superperiod, (unlike group-1 or 2, group-3 does not consists of a reflex-symmetrical pair of correctors). The machine functions for one superperiod are shown on Fig. 5. The location of the correctors are also indicated on th figure.

Calibration measurements were performed twice, two months apart under the same conditions in the X-ray ring.

Figs. 6-7 show the 2 sets of horizontal and vertical conversion factors. Data corresponding to the #1, #2, #3, #4 and #5 correctors are marked by $\square$, $\circ$, $\bullet$, Δ and ∇ . In addition to the individual data, the conversion factors, averaged over the m-th correctors in all superperiods and their error are also shown on the figures.

The $\bar{C} \pm \delta \bar{C}$ average and the σ standard deviation for each of the 3 groups of magnets as well as $\bar{C}$ at the end-point of the superperiods are shown in Table-3. (There are no correctors symmetrically positioned around the reflex-point of the superperiods in the X-ray ring).

Table-3

		2.5 Gev					
		case-1			case-2		
		j=1,5 end	j=2,4	j=3	j=1,5 end	j=2,4	j=3
H	$\bar{C}$	.35±.00	.47±.01	.22±.01	.34±.00	.48±.01	.22±.01
O	σ	±.05	±.06	±.03	±.05	±.10	±.03
R	$\bar{C}$	.02±.00			.02±.00		
V	$\bar{C}$	.37±.01	.36±.01	.24±.02	.37±.01	.38±.01	.25±.01
E	σ	±.04	±.04	±.02	±.04	±.04	±.02
R	$\bar{C}$	.00±.01			.00±.01		

Fig. 7 suggests a vertical superperiodicity of 4 instead of 8; the $C_y^{1,5}$ and $C_y^{2,4}$ (high β locations) seem to be $\approx 20\%$ higher in every second superperiod with a corresponding $\delta\bar{C}/\bar{C} = \pm 2\%$. There is no systematic difference in the value of C_y^3 (low β locations). This is confirmed by the fact, that $\sigma \approx \delta\bar{C}$ for the $j=3$ correctors, as seen from Table-3. Also note, that $\bar{C} \approx 0$ at the end-points.

Horizontally, one can see from Fig. 6 that there is a large first harmonic pattern in the conversion factors of each group of correctors. Table-3 shows a significant spread in the data ($\sigma \geq 3 \cdot \delta\bar{C}$), as well as $\bar{C} = .02$. Assuming $\beta_x = 12.5$ m at the location of the group-1 correctors, as model calculations indicate, the corresponding β is 1.7.

CONCLUSION

The ratios of the C conversion factors for identical correctors contain information on the ratios of the β values at the corrector locations, yielding information on the symmetry of the ring. This method of studying the symmetry properties of the ring is very sensitive and its accuracy depends only on the accuracy and reliability of orbit measurements. Any not directly modelled asymmetry in the ring is accounted for in orbit manipulations (correction or local distortion) through the use of the measured C conversion factors.

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Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig. 7