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CONSIDERATIONS ON AD OPTICS IMPROVEMENT BASED ON RESPONSE MATRIX MEASUREMENTS

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Considerations on AD Optics Improvement Based on Response Matrix Measurements

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1 Introduction

Orbit response measurements, i.e. the change of orbit when a dipole is excited, contain a valuable information on the optics characteristics of a synchrotron. Systematic orbit response measurements have been applied to determine the optics of several machines [1], [2]. In 1999 orbit response measurements were performed for AD and allowed to reveal a faulty behaviour of a special "half" quadrupole. In previous paper [3] orbit response measurements were used to determine the phases at the pick-up and dipole locations, which in turn allowed to refine the accelerator model by fitting quadrupole strengths. Here, the gradients of quadrupoles were determined directly from the measured data. The two methods are well compatible and complimentary:

- if lattice parameters are determined from response data and optics perturbations are larger than the error of measurements, they will be detected by both methods
- when magnetic element parameters are varied to fit the measured data, an improved model of machine is obtained in one step. However, if the model is not compatible with the perturbations (e.g. if faulty behaviour of the "half" quadrupole would not be taken into account), the discrepancy will not be discovered
- the method based on fitting phase advances with a general accelerator code like MAD [4], contains all the possible sources of perturbation after first step. Only random errors (noise of pick-ups etc.) put limits on the accuracy of the further investigations. At the second step, when the errors in machine parameters have to be discovered, it is very flexible allowing to run MAD program with different sets of variables
- the method presented in this report is based on "one step" fitting and keeps all intermediate information easy available, that can be successfully used for further analysis of a descrepancy between the machine model and the measurements ("bad" pick-ups, corrupted data due to beam losses etc.)

In the present report, a machine model is developped directly from a measured orbit response. The accepatance reduction of AD caused by deviations of machine parameters from their design values is estimated and compared with measurements. The possible mechanism of a losses at low energies is discussed.

2 Description of the method

The response of orbit x_{ij}^{meas} of pick-up at the position i to an excitation by the corrector with unit strength at position j differs from its theoretical value

$$x_{ij}^{th} = \frac{\sqrt{\beta_x^i \beta_x^j}\, cos(\mid \mu_x^i - \mu_x^j \mid - \pi Q_x)}{2sin(\pi Q_x)} + D_x^i\, \delta p_j \tag{1}$$

due to a deviation of magnetic element parameters λ_i from their design values. Here β_x, μ_x and D_x are beta function, phase advance and dispersion, Q_x is the betatron tune and δp_j is the change in momentum produced by corrector with number j. The deviations of parameters from their design values include an errors in a quadrupole strengths, their positions, as well as positions of pick-ups and correctors etc. In reality, a pick-up gains g_i and corrector strengths h_j also are different from 1, contributing to a difference between measurements and model. In general, a measured data can be written as

$$x_{ij}^{meas} = g_j \cdot x_{ij}^{th}(\lambda_1 + \delta\lambda_1, \lambda_2 + \delta\lambda_2, ..., \lambda_n + \delta\lambda_n) \cdot h_j. \tag{2}$$

Expanding right hand in (2) in series and keeping only first order terms, one gets

$$x_{ij}^{meas} - x_{ij}^{th} = \delta g_i \cdot x_{ij}^{th} + \delta h_j \cdot x_{ij}^{th} + \sum_n \frac{\partial x_{ij}^{th}}{\partial \lambda_n}\, \delta\lambda_n, \tag{3}$$

where $\delta g_i = g_i - 1,\ \delta h_i = h_i - 1$. For AD, orbit measurements are performed with RF cavity on, thus maintaining the same revolution frequency. In this case $\delta p_j = D_x^j/(\eta L), \eta = 1/\gamma^2 - \alpha, \alpha$ is momentum compaction, L is a circumference of an accelerator [3].The coefficients $\partial x_{ij}^{th}/\partial \lambda_n$ can be caclulated by a general accelerator program like MAD, which has been used for this studies.

In AD there are 32 horizontal and 27 vertical pick-ups, as well as 18 horizontal and 7 vertical orbit correctors, available for measurements. The particle motion considered uncoupled, hence one has 32×18+27×7=765 readings. With the goal of improving machine optics as a first priority only errors in quadrupole strengths along with pick-up gains and corrector strengths have been taken into account. Optics of AD can be well described by 11 independant quadrupole families. The first members of them are QDN01, QFN04, QFN54, QDN05, QDN53, QFW06, QDW07, QFW08, QDW09, QDN27, QFN29A. Families with "half" quadrupoles QFN54 and QDN53 has no other members. Quadrupoles QDN01, QFN04, and QD05 have the same construction and the same power supply but different gradients due to different number of spires. For the theoretical model of optics, the ratios between them has been taken from the magnetization curves measured in lab. The same is true for the quadrupoles QDW07 and QDW09. These ratios can be verified by use of respose matrix measurements. Totally, one has 32+27+25+11=95 fitting parameters with reasonable statistics for their definition.

3 Optics at 3.57 GeV/c

The relative differences between the gradients obtained by fitting orbit response data and the gradients of the designed optics are given in Table 1. The discrepancies are less than 1%, resulting to AD top energy optics very close to the design one. The ratios between strengths of quadrupoles connecting to the same power supply are given in Table 2. The orbit response to the excitation of one corrector and residual descrepancy between measurement and refined (i.e. found by fitting) model is shown in Fig. 1.

QDN01	QFN04	QFN54	QDN05	QDN53	QFN06	QDN07	QFN08	QDN09	QFN29A	QDN27
0.02	0.56	-0.31	-0.12	0.34	-0.21	-0.69	-0.41	-0.04	-0.89	0.83

Table 1: Deviations of quadrupole strengths from their design values at top energy in percent. A positive value means that in the real machine the strength is larger than for design one.

The errors in quadrupole strengths produce linear optics distortions resulting in a reduction of the machine acceptance. An acceptance of machine model (i.e. found for quadrupole setting given in Table 1) in the horizontal plane is 5.1% (11 π mm mrad) smaller, and in the vertical plane is 2.7% (5 π mm mrad) larger than that of the design optics. Here and below an acceptance is defined as minimum of ratio a^2/β throughout accelerator (a is an aperture limitation). During the commissioning the horizontal tune was slightly shifted away from the fifth order resonance $5Q_x$=27. The tunes of the machine model (Q_x=5.384 and Q_y=5.367) are in a good agreement with that ones found by direct measurements.

To correct optics distortions and keep tunes Q_x=5.385, Q_y=5.367 (instead of design values Q_x=5.39 and Q_y=5.37), modified optics which also takes into account more precise ratios between quadrupoles (QD1, QF4, and QD5) and (QD7 and QD9) has been prepared. Then it was applied to fit the measurements, with results given in Table 3. For this step, only seven really available independent quadrupole families have been kept.

	$\frac{G_{QF04}}{G_{QD01}}$	$\frac{G_{QD05}}{G_{QD01}}$	$\frac{G_{QD09}}{G_{QD07}}$
power supply	QMAIN1	QMAIN1	Trim2
from fitting procedure	0.9198	0.8256	0.7860
from magnetic measurements	0.9149	0.8268	0.7809

Table 2: The ratios between quadrupole strengths for the families connecting to the same power supply.

The relative deviations of the gradients in quadrupoles QD1, QF4, and QD5 (and other of the same type) from the design ones are slightly different, while powered by the same power supply. This means that ratios of their strengths taken from measurements made in laboratory and used in AD optics model, are no longer valid in the machine. Due to the error in the QF4 and QD5 family strengths their bending angles differ from the design ones of 30 mrad and 18 mrad respectively. These errors (0.17 mrad and -0.02 mrad) produce closed orbit excursion with maximum value $x_{c.o.}^{max}$ = 3.4 mm. To eliminate them one has to realign QF4 (and other members of this family) by moving inside of machine in 0.4mm.

QDN01 0.11	QFNF54 -0.84	QFW06 -0.24	QDW07 -0.38	QFW08 0.34	QFN29A -0.78	QDN27 0.53
QMAIN1 -1.9 A	Trim5 17.1 A	Trim1 6.4 A	Trim2 9.7 A	Trim3 8.2 A	Trim4 17.5 A	QMAIN2 -4.1 A

Table 3: The same convention as in Table 1. The two last lines show how much current has to be added to bring optics of the real machine to the design optics.

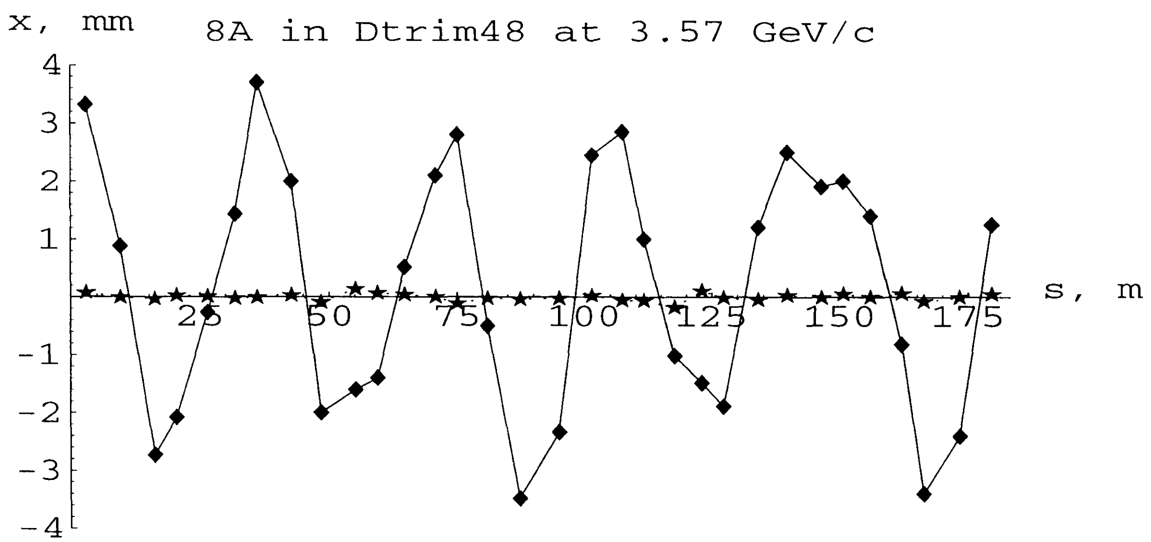

Figure 1: The measured orbit response caused by excitation of one corrector is shown by squares. The descrepancy between it and that one found by fitting is shown by stars.

4 Optics at 2 GeV/c

4.1 Q_x / Q_y = 5.39 / 5.37

The results of fitting are given in Table 4. One of the measurements has been excluded (excitation of orbit by the vertical corrector DVT5408 caused beam losses).

QDN01	QFN04	QFN54	QDN05	QDN53	QFN06	QDN07	QFN08	QDN09	QFN29A	QDN27
2.78	1.78	-7.09	-1.45	-1.53	-2.71	0.05	0.61	-1.28	-0.14	-0.57

Table 4: Deviations of quadrupole strengths from their theoretical values in percent at 2 GeV/c for the optics with tunes Q_x / Q_y = 5.39 / 5.37. A positive value means that in the machine the strength is larger than the design one.

The main feature of 2 GeV/c optics as it was already pointed out [3] that the "half" quadrupole QFN54 is about 9% weaker than other members of the same family. The gradient deviations from their design values in other families are also significant. The lattice functions of the design optics and the machine model are shown in Fig. 2 and 3. The relative difference between beta functions for these two optics is up to 50% in the horizontal plane and up to 20% in the vertical plane (Fig. 4 and 5).

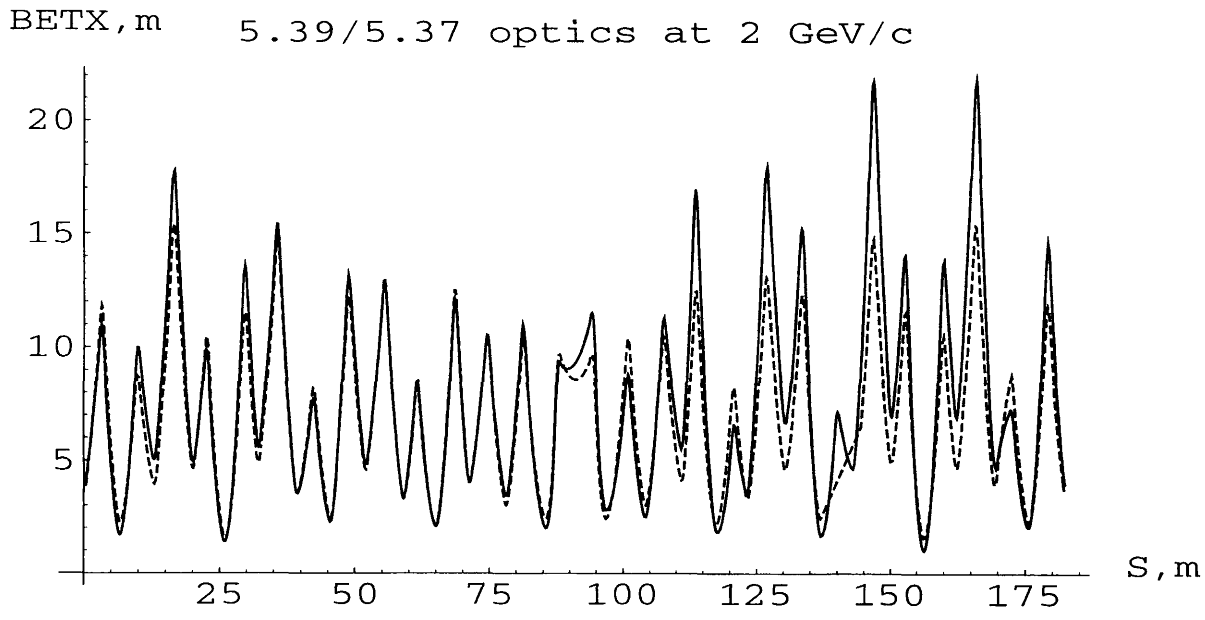

Figure 2: Horizontal beta function in AD. For the machine model it is shown by a solid line, for the design optics it is shown by a dashed line.

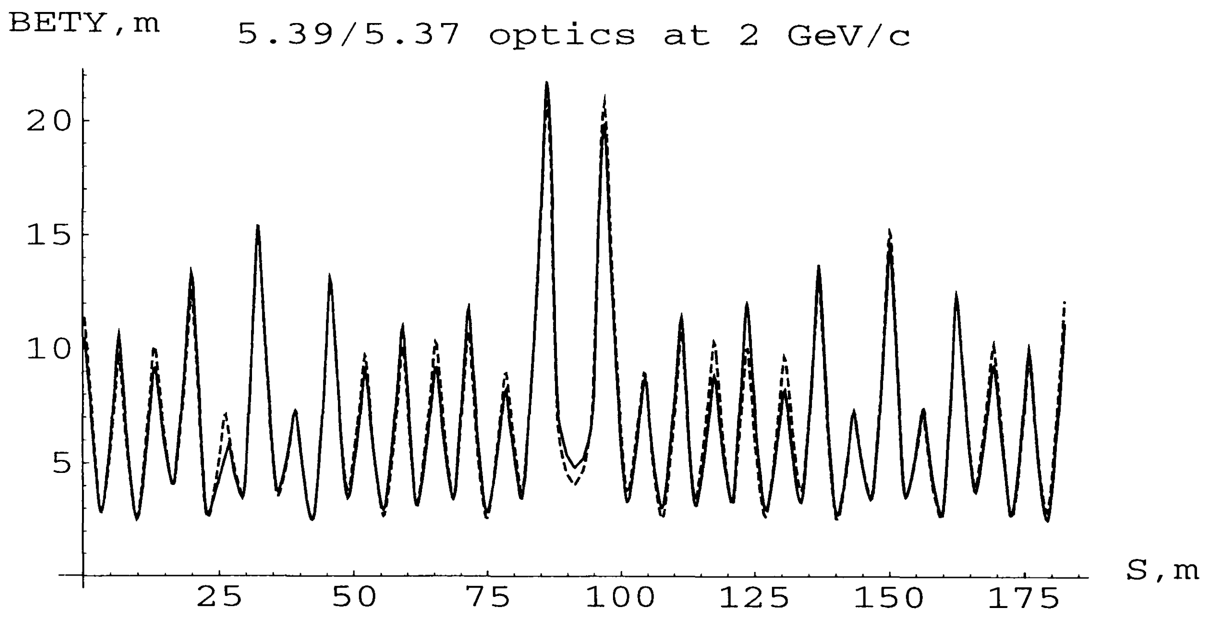

Figure 3: Vertical beta function in AD. The same notation as for Fig. 2

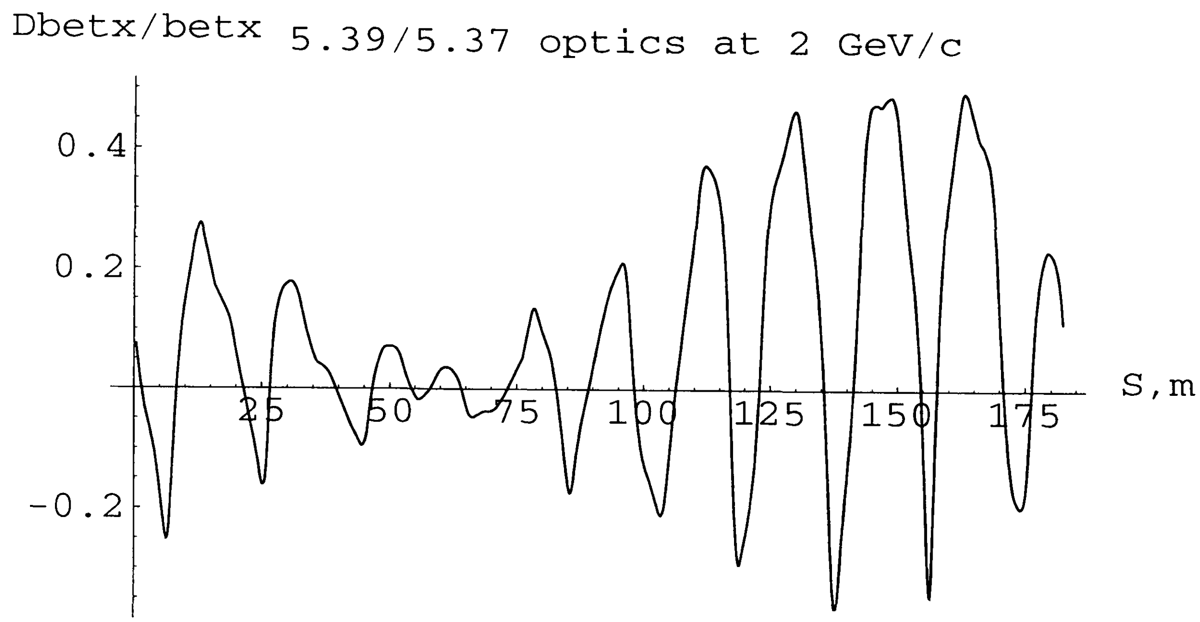

Figure 4: The relative deviation $(\beta_x^{fit} - \beta_x^{th})/\beta_x^{th}$ of the horizontal beta function of the machine model β_x^{fit} from the design value β_x^{th}.

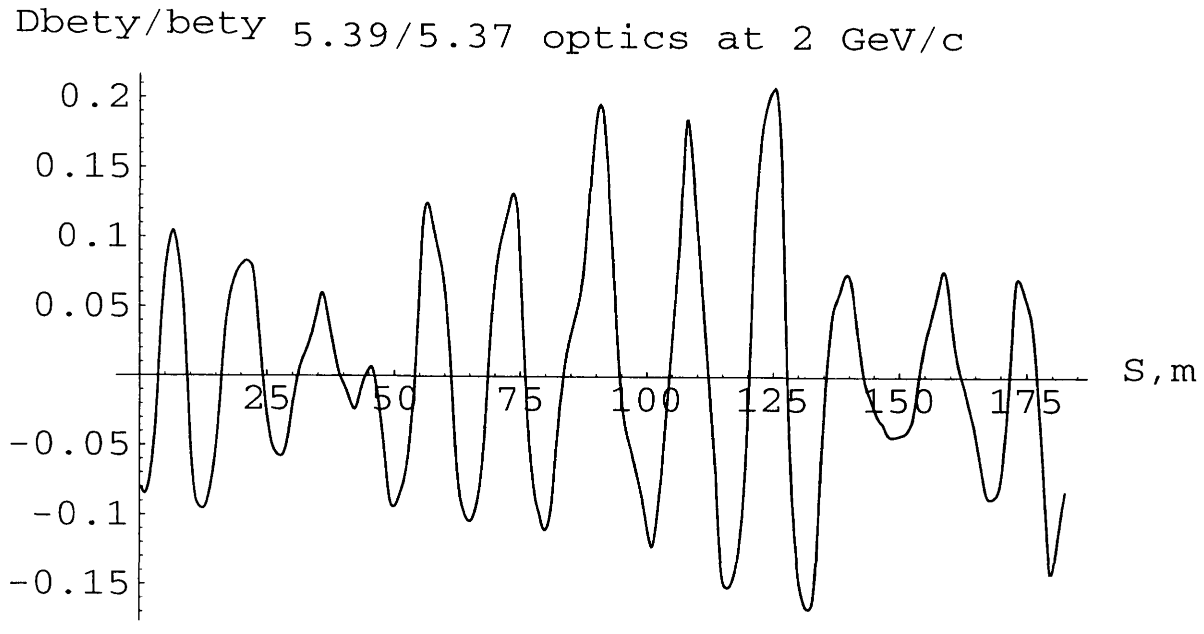

Figure 5: Vertical plane. The same notation as in Fig. 4.

The horizontal acceptance of the machine model is reduced in 17% and two thirds of this reduction comes from the QFN54 deviation. The measured horizontal acceptance is about 130 π mm mrad, about 20% less than that one at top energy (160 to 170 π mm mrad) in a good agreement with machine model. The vertical acceptance is 6% bigger than that of the design optics. The measured vertical acceptance is approximately the same as at top energy. To make the gradient in the "half" quadrupole QFN54 the same as for the QFN04 and other quadrupoles of this family, additional power supply will be available. The difference between the "half" quadrupole QDN53 and other members of the same family (marked QD5 in Table 4) is 0.1%. For a big deviation of a machine parameters from their design values (as in the case of optics at 2 GeV/c), coefficients $\partial x_{ij}^{th}/\partial\lambda_n$ found by expansion around design values λ_n^{th} are no more valid and the fitting procedure must be repeated again till its convergence.

4.2 Q_x / Q_y = 5.45 / 5.42

These measurements are more noisy. The reference orbit fluctuations are about 0.15 mm, that is 4 times larger than for the previous case. Due to this residual descrepancy between measurements and machine model is two times larger than for optics with Q_x= 5.39 and Q_y=5.37. The data acquired by the excitation of two correctors have been excluded from the fitting due to losses during the measurements. The results for the relative quadrupole deviations from their design values are given in Table 5 and 6.

QDN01	QFN04	QFN54	QDN05	QDN53	QFN06	QDN07	QFN08	QDN09	QFN29A	QDN27
-1.33	0.89	-9.63	0.94	-1.10	-0.70	0.17	1.39	0.80	-0.38	0.30

Table 5: Deviations of quadrupole strengths from their design values in percent at 2 GeV/c for the optics with tunes Q_x / Q_y = 5.45 / 5.42. A positive value means that in the real machine the strength is larger than the design value.

The gradient of QFN54 is 10.5% smaller than that one of QFN04 and other members of this family. The gradient of QDN53 is 2% smaller than that of QDN05. This is a bit larger than for optics with tunes Q_x / Q_y = 5.39 / 5.37, where these values are 9% and 0.1% respectively. The horizontal acceptance reduction (as defined above) due to distortion of the linear optics is about 38%, that is twice larger than for the optics with tunes Q_x=5.39 and Q_y=5.37. Again about two thirds of this reduction comes from the weakness of "half" quadrupole QFN54. The measured horizontal acceptance is about 90 $\pi mmmrad$, and its reduction about 45%. The bigger measured reduction of the acceptance can be explaned by bigger residual orbit excursion at 2 GeV/c, compared with top energy. The vertical acceptance of the machine model is approximately the same as for the design optics. The lattice functions are shown in Fig. 6 and 7. They are in a good agreement with that found in [3].

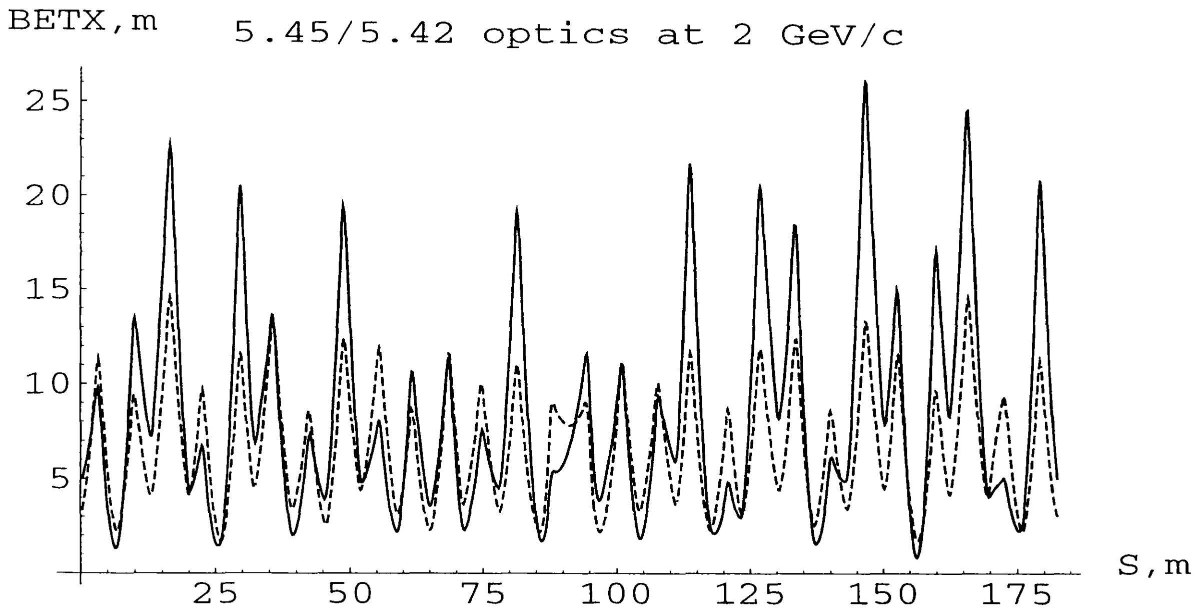

Figure 6: Horizontal beta function in AD. For the machine model it is shown by a solid line, for the design optics it is shown by a dashed line.

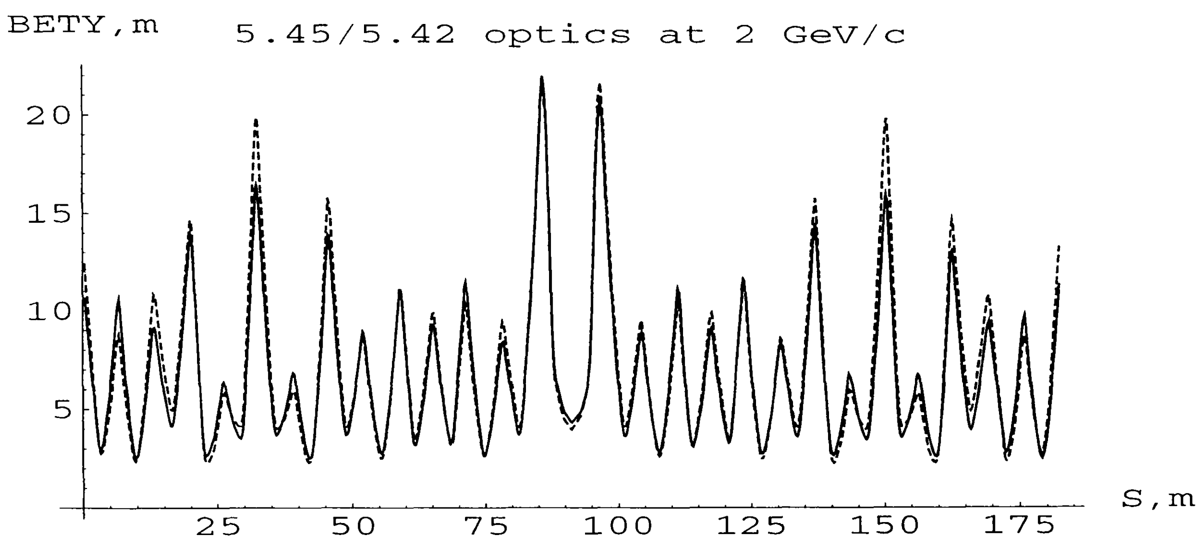

Figure 7: Vertical beta function around AD. The same notation as for Fig. 6.

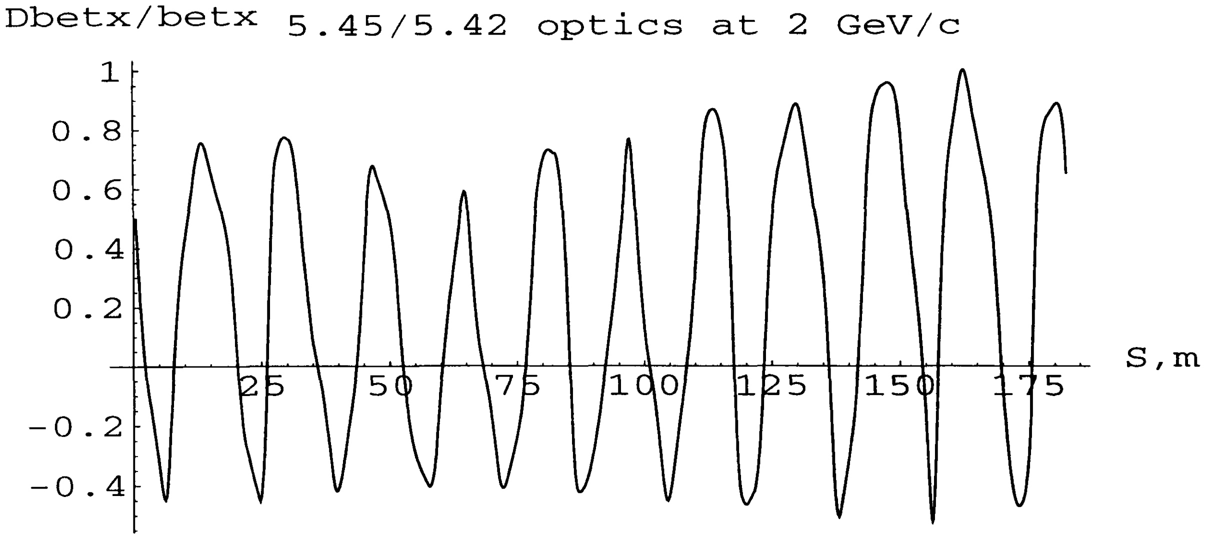

Figure 8: The relative deviation $(\beta_x^{fit} - \beta_x^{th})/\beta_x^{th}$ of the horizontal beta function of the machine model β_x^{fit} from the design value β_x^{th}.

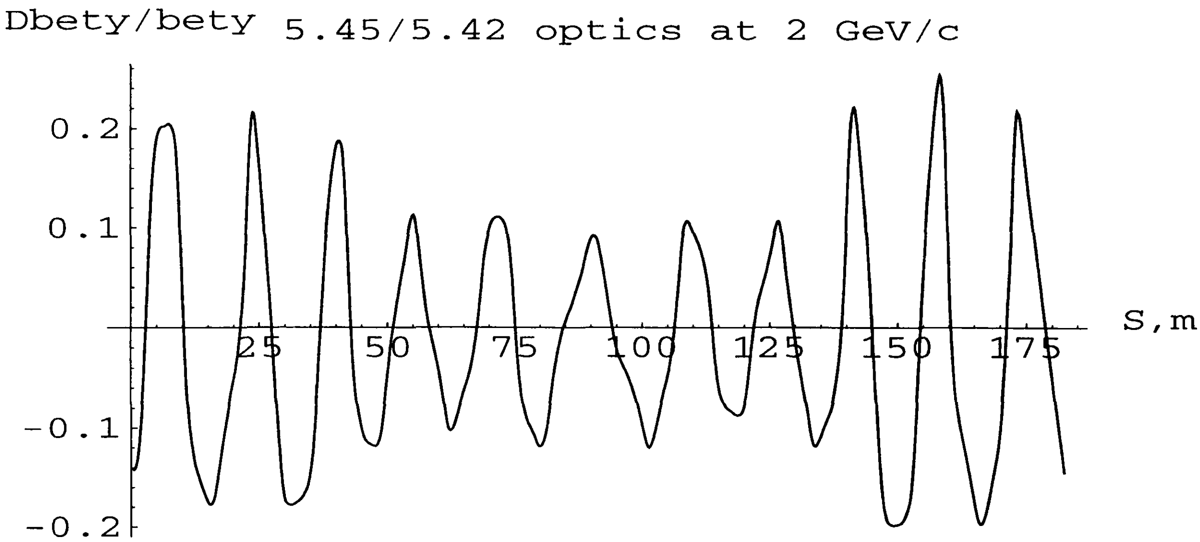

Figure 9: Vertical plane. The same notation as for Fig. 8.

The deviations of beta functions from their theoretical values for optics with tunes Q_x / Q_y = 5.45 / 5.42 is up to 100 % in the horizontal plane, approximately twice bigger than for the optics with tunes Q_x / Q_y = 5.39 / 5.37, in agreement with theoretical prediction. For the vertical plane the deviation is about 30 % , that is about 1.5 times bigger than for optics with tunes Q_x / Q_y = 5.39 / 5.37, also in agreement with theory.

The study of optics found by fitting, in addition to strongly reduced acceptance shows that it is much more sensitive in the horizontal plane to gradient errors than the theoretical optics. For example, 0.5 % error in Trim1 (members of family are QF6 etc.) produce change in the horizontal tune $22{\cdot}10^{-3}$. For the design optics this value is $13{\cdot}10^{-3}$. The maximum beta function throughout machine is 38m for the measured optics and 16m for the nominal one. For other quadrupole family powered by Trim3 (quadrupoles QF8 etc.) results are similar. Error in 0.5 % produce change in the horizontal tune $23{\cdot}10^{-3}$ and maximum beta function in machine 40m, while for the nominal optics they are $14{\cdot}10^{-3}$ and 16.5m respectively. This can explain big losses exactly below 300 MeV/c, when due to different tracking (or pulsing) of quadrupoles additional variations in quadrupole strengths are appeared.

The results of fitting at 2 GeV/c show that the ratios between gradients in quadrupoles having the same power supply and different number of spires are close to that found from the magnetization curves (shown in Table 6). But they are far from the values at top energy. Due to this bending angles of combined function magnets QFN04 (and others) in 30 mrad and QDN05 (and others) in 18 mrad correctly established at top energy can't be maintained through all the cycle. Hence, optics at low momentum must be prepared in a way to minimize adverse effect of closed orbit excursion produced by these quadrupoles. By the proper choice of the strength of family (QDN01, QFN02, etc.) this adverse close orbit excursion can be reduced to 1mm.

	$\frac{G_{QF04}}{G_{QD01}}$	$\frac{G_{QD05}}{G_{QD01}}$	$\frac{G_{QD09}}{G_{QD07}}$
power supply	QMAIN1	QMAIN1	Trim2
from the machine model with Q_x / Q_y = 5.39 / 5.37	0.9060	0.7927	0.7704
from the machine model with Q_x / Q_y = 5.45 / 5.42	0.9055	0.7956	0.7692
from magnetic measurements	0.8987	0.7909	0.7656

Table 6: The ratios between quadrupole strengths at 2 GeV/c for the families connecting to the same power supply.

5 Conclusions

The method based on "one step" fitting the response matrix of machine can explain reduction of AD acceptance at intermediate and low energies, as well as significant losses during deceleration at low energies and can be succesfully used both for improving of the optics model and adjustment of machine optics.

References

[1] W. J. Corbett, M. J. Lee, and V. Ziemann. A Fast Model-Calibration Procedure for Storage Rings, SLAC-PUB-6111, May 1993.

[2] J. Safranek. Beam-Based Lattice Diagnostics. In: Beam Measurement. Proceedings of the Joint US-CERN-Japan-Russia School on Particle Accelerators, Montreux 11-20 1998.

[3] P. Beloshitsky and C. Carli. Optics Investigation of AD by means of Orbit response Matrix (to be published)

[4] H. Grote, F. Iselin, The MAD Program, Version 8.19, User's Reference Manual. CERN/SL/90-13(AP), (Rev.5), 1996.

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