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FIRST EXPERIENCE OF APPLYING LOCO FOR OPTICS AT COSY

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Abstract

COSY is a cooler synchrotron designed for internal target hadron physics experiments, equipped with both electron cooling system and stochastic cooling system. During the past couple of years, COSY has been evolved into an ideal test facility for accelerator technology development as well as detector development for the Facility of Anti-proton and Ion Research at Darmstadt (FAIR). In addition, the test ground for exploring the feasibility of a storage ring based Electric Dipole Moment (EDM) measurement. The proposed precursor experiment of a direct measurement of the EDM of the deuteron at COSY using an RF wien filter by the Juelich Electric Dipole moment Investigation (JEDI) requests significant improvement of beam based measurements as well as beam control. In this paper, first results of measured linear optics based on Orbit Response Matrix (ORM) by AT-LOCO code are reported. Simulation studies are also discussed.

DESCRIPTION OF THE FACILITY

COSY is a cooler synchrotron and storage ring[1], which covers the whole momentum range from 600 MeV/c up to 3.3 GeV/c and delivers up to 3×10^{10} protons. Electron cooling is applied up to 645 MeV/c. Stochastic cooling will enhance the beam quality in the range from 1.5 to 3.3 GeV/c. The ion sources are a H_2^+, H^-, D^- and a H^- polarized ion source. Sixteen quadrupoles in each 40 m long straight section of COSY grouped as four triplets allow the ion optics to be tuned such that the sections act as telescopes with a 1:1 imaging giving either a π or a 2π phase advance. The arc sections have a length of 52 meters each. They are composed of three identical elements that have in themselves a mirror symmetry. A half-cell has a QF-bend-QD-bend structure with the option to interchange focusing-defocusing for added flexibility in adjusting the tune. This structure leads to a six fold symmetry for the total magnetic lattice of the ring. In total 18 sextupoles are installed. They can be grouped into 11 families. EDM is a high precision task for the COSY facility, Because of all this, a good agreement between the real optics and the model is essential for the COSY to achieve the maximum performance. During the commissioning of the COSY from Sept. to Nov. 2015, we used the Linear Optics from Closed Orbits (LOCO)[3] to calculate the beam parameters of COSY.

In this paper, we present the results of our first attempt to use LOCO at the COSY, including a brief introduction of adapted LOCO for COSY, some simulation work and the analysis result from real measurement.

ORM BASED ON LOCO AND APPROXIMATING

The ORM has been used by many accelerators around the world to find calibration errors and correct the optics functions. The orbit response matrix (ORM) is defined as:

$$\begin{pmatrix}\Delta X\\ \Delta Y\end{pmatrix} = M\begin{pmatrix}\Delta\theta_x\\ \Delta\theta_y\end{pmatrix} \quad (1)$$

where $\Delta\theta_x$ and $\Delta\theta_y$ are the changes in strength of horizontal and vertical correctors respectively, ΔX and ΔY are the orbit perturbations at the BPMs. M is an $m \times n$ matrix, where m is the number of BPMs, and n is the number of horizontal and vertical correctors.

In LOCO code the difference between the measured and model response matrices as (2) is minimized by varying the quadrupole strengths, corrector kicks and BPM gains in model.

$$\chi^2 = \sum_{i,j}\frac{\left(M_{mod,ij}-M_{mea,ij}\right)^2}{\sigma_i^2} \equiv V_{ij}^2 \quad (2)$$

where σ_i is the measured noise level for BPMs.

The LOCO is developed for light source, which is used for high energy electron, not according with the COSY ring. So there is necessary to make some adapted and approximating in the code.

Because the dispersion in COSY is quite big, the calculation of response matrix could not ignore the dispersion term. So the model response matrix modified by the energy change at the corrector magnets should be:

$$\Delta x_j = \frac{\sqrt{\beta_{xi}\beta_{xj}}}{2\sin\pi Q_x}\cos\left(\pi Q_x - \left|\Delta\psi_{xij}\right|\right)\theta_{xi} - \frac{D_i D_j}{\eta L}\theta_{xi} \quad (3)$$

Because of $\eta = \alpha_p - \frac{1}{\gamma^2} = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$, LOCO use (4) as a approximation for high energy electron beam when $\gamma \gg 1$.

$$\Delta x_j = \frac{\sqrt{\beta_{xi}\beta_{xj}}}{2\sin\pi Q_x}\cos\left(\pi Q_x - \left|\Delta\psi_{xij}\right|\right)\theta_{xi} - \frac{D_i D_j}{\alpha_p L}\theta_{xi} \quad (4)$$

The COSY is a medium energy accelerator, the beam speed is much lower than light source (β<<1). So the approximation not work and the γ must be calculated in this progress. So some change in LOCO ORM calculation is corrected as (3), and η is taken in with the COSY beam and energy.

In using LOCO, with the measured or simulated data and the initial parameters we calculate the initial V_{ij} first, solving the change of all the parameters from quadrupole, corrector, BPM and etc. by singular value decomposition to minimize χ^2, modifying the parameters and repeating

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above procedure until the residual errors of M_{mea} and M_{mod} converge to the noise level of BPM. With the parameters derived from LOCO, the model optics can predict the real one, and after the parameters are corrected, the design optics can be restored.

SIMULATION STUDIES

With such a procedure, we make simulation to test the code and give an estimate for the real measurement. COSY ring has 31 horizontal BPMs, 30 vertical BPMs, 21 horizontal correctors and 19 vertical correctors, however the arrangement of BPMs and correctors is not well distributed between quadrupole magnets. In straight section there is no BPM or corrector between four quadrupole magnets, and the COSY 56 quadrupole magnets with 14 PS are grouped to 14 families for every 4 magnets, which predicted fitting quadrupole strength will be difficult. So it is essential to evaluate the progress effective by simulation.

In order to accord to the real machine, the error setting in simulation covers some common random errors.in practical accelerator which is set as choice as below:

- Quadrupole magnet field error. (Strength STD: 2%)
  1. 14 independent errors each for 4 magnets in one family;
  2. 56 independent errors for each magnet.
- Kick Gain: 5% or without error
- BPM Gain: 2% or without error
- BPM Noise: ±1mm or without error

After error setting, the simulated response matrix from tracking is taken into the LOCO fitting. The parameter used to be fit is include BPM and corrector gains, and quadrupole strength. Quadrupole magnet in fit is divided into two choice: 56 independent magnet or 14 families each include 4 magnets. All above setting is shown in Table 1.

The MODE A6, which take all errors set in, is most closed to real measurement in our simulation. After calculation by LOCO, that Chi-square is convergent to BPM noise limit. The average result from many seeds show that:

- The STD of corrector gains error between set and result is 4.65%. (good)
- The STD of BPM gains error between set and result is 1.35%. (good)
- The quality of quadrupole strength fitting is bad, result show in Figure 1.
- The difference between setting and fitting beta function smaller than 4%, which is acceptable for now (Figure 2).

The quadrupole fitting quality is not good because of the BPM amount and arrangement. If the storage ring has more BPM, for example, 56 BPMs each closed to one quadrupole (MODE B1), the quadrupole fitting could get good result. MODE B2 with 28+28 BPMs, which is less than the current machine but rearrange the BPM position, also could get the acceptable quadrupole magnet fitting result. So BPM upgrade may be an important subject for future COSY to satisfy EDM.

Table 1 Simulation Summary of Different Condition

Model	A							B	
Mode	A0	A1	A2	A3	A4	A5	A6	B1	B2
BPM amount	31+30							56+56	28+28
Quad Fit Family	\	14*4	14*4	56*1	14*4	56*1	56*1	56*1	56*1
Error Set									
Quad Error Family	\	14*4	14*4	14*4	56*1	56*1	56*1	56*1	56*1
Quad Error	\	±2%	±2%	±2%	±2%	±2%	±2%	±2%	±2%
Kick Error	\	\	±5%	±5%	±5%	\	±5%	±5%	±5%
BPM Gain	\	\	±2%	±2%	±2%	\	±2%	±2%	±2%
BPM Noise(mm)	\	\	\	\	\	\	±1mm	±1mm	±1mm
Fit Quality: STD=std((FitValues-SetError)./Strength); PPV=Peak Peak Value;									
ChiSquare	\	Perfect	Perfect	Good	0.3168	Perfect	0.917954	0.888515	1.0179
Quad STD	\	Perfect	Perfect	Bad	Bad	Perfect	Bad	0.8620%	3.993%
Kick STD	\	\	<0.2%	1.2%	2.0539%	\	4.65%	0.2865%	0.913%
Gain STD	\	\	<0.2%	1%	1.98%	\	1.3512%	1.5212%	1.674%
Beta PPV	\	Perfect	Perfect	Some 1%~10%; Mostly Good.	~10%	Perfect	4%	2%	4%~16 %

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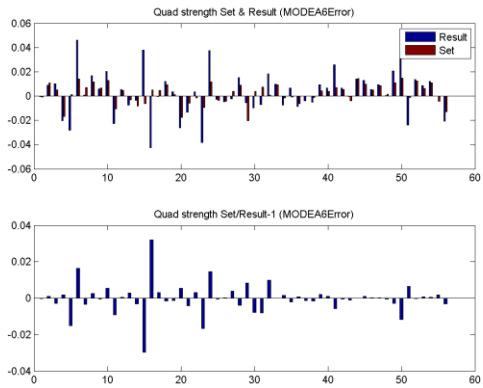

Figure 1. Quadrupole setting and fitting result of MODE A6.

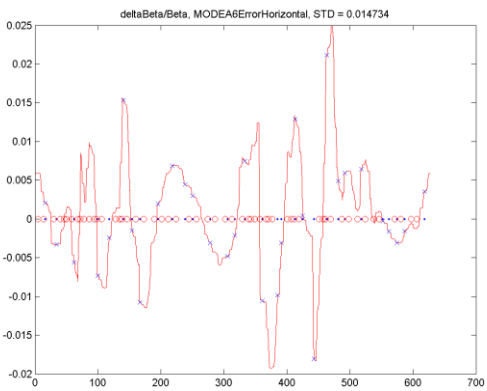

Figure 2. Horizontal Beta beat of MODE A6

RESULT FROM MEASUREMENT

The real measurement data was taken at Nov. 2015. Some data measured and calculated with different setting. Here, we only present one single result.

In this case, the parameters listed below were varied in fitting the model to the measured response matrix:

- 24+23(H/V) BPMs gains;
- 18+17 horizontal corrector magnet kicks;
- 24 energy shifts at the horizontal correctors;
- 56 strengths of quadrupoles;

The comparison of measured response matrix and difference between the measured and fitted model response matrix are shown in Figure 3. Note that after fitting, the residual orbit is much smaller.

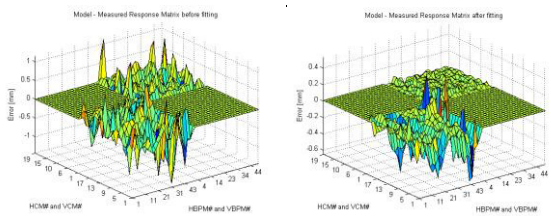

Figure 3 difference between measured and model before (left) and after fitted by LOCO (right).

After the result parameters determined by LOCO were applied to the COSY nominal lattice, optics measurement was calculated by AT. The betabeat measurement result is shown in Figure 4. The betabeat between measurement and design beta functions are within 0.7~1.4 in *x* plane and 0.85~1.25 in *y* plane.

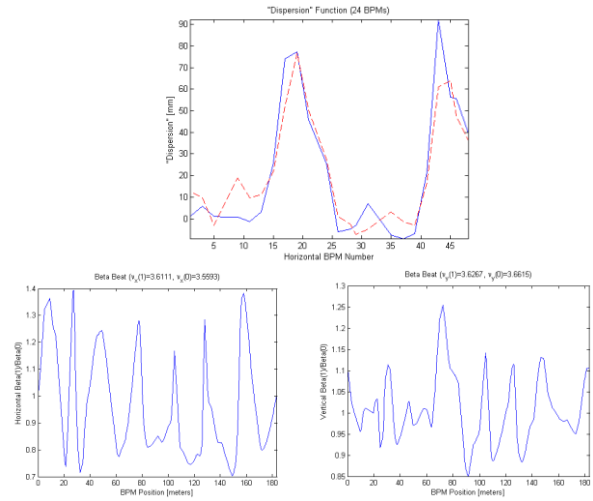

Figure 4. The optics parameters result. Upper: Dispersion. Lower: Betabeat

SUMMARY AND PERSPECTIVES

EDM requests significant improvement of COSY beam based measurements as well as beam control. As the first experience of applying ORM method, we present the results of some simulation work and the analysis result from real measurement. From the real measurement, we got the optics function such as beta function and horizontal dispersion. The quadrupole magnet strength correction is failed in simulation, which means the BPM improvement should be an important part for COSY upgrade.

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