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Quad Family Centering

I. Pinayev
NSLS, Brookhaven National Laboratory, Upton, NY

National Synchrotron Light Source
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973
www.bnl.gov

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Igor Pinayev, NSLS

It is well known that beam position monitors (BPM) utilizing signals from pick-up electrodes (PUE) provide good resolution and relative accuracy. The absolute accuracy (i.e. position of the orbit in the vacuum chamber) is not very good due to the various reasons. To overcome the limitation it was suggested to use magnetic centers of quadrupoles for the calibration of the BPM [1].

The method is based variation of the individual quadrupole strength by few percent. If the center of the beam does not come through the magnetic center of the quadrupole then, due to non-zero field integral, the beam is experiencing deflection θ, proportional to the orbit deviation from the center (x,y), quadrupole strength K1, and magnetic length of the quadrupole L_{mag}. The sign depends on the quadrupole type (focusing or defocusing) and observation plane (vertical or horizontal).

$$\theta_{x,y} = \pm x, y\, K1\, L_{mag}$$

With the change of the quadrupole's strength K1 the proportionality coefficient changes and the equilibrium orbit varies. The orbit excursion provides data for obtaining value of the orbit offset in the quadrupole. Orbit can be found from the equations below:

$$x(s) = \frac{\theta_x}{2}\sqrt{\beta_x(0)\beta_x(s)}\,\frac{\cos\left[\left|\varphi_x(s)-\varphi_x(0)\right| - \pi\nu_x\right]}{\sin \pi\nu_x}$$

$$y(s) = \frac{\theta_y}{2}\sqrt{\beta_y(0)\beta_y(s)}\,\frac{\cos\left[\left|\varphi_y(s)-\varphi_y(0)\right| - \pi\nu_y\right]}{\sin \pi\nu_y}$$

where $\beta_{x,y}$ are betatron functions, $\varphi_{x,y}$ are betatron phase advances, *s* is longitudinal coordinate with *s=0* corresponding to quadrupole location, and $\nu_{x,y}$ are betatron tunes.

If the closed orbit were stable then kick change would be $\delta\theta_{x,y} = \pm x, y\, \delta K1\, L_{mag}$. However, for the storage rings one also needs to take into account the beam displacement in the quadrupole and the variation of the orbit kick induced by the quadrupole strength change is [2]:

$$\Delta\theta_{x,y} = \frac{\pm x, y\, L_{mag}\, \Delta K1}{1 + K1\, L_{mag}\, \beta_{x,y} / (2\tan \pi\nu_{x,y})}$$

By varying orbit at the particular quadrupole using local bumps or nearby correctors one can find beam orbit which has minimal variations with changing quadrupole strength. This procedure allows determination of the offset of the quadrupole center relatively to the BPM center. The method can be easily implemented for the accelerators with quadrupoles with individual power supplies. For the storage ring with power supply feeding a quadrupole family it was suggested to utilize current shunts, which allow reduction of current in a single quadrupole without affecting strength of the others [1, 2].

In the method suggested below the variation of the quadrupole's kick $\delta\theta$ is compensated by a built-in or adjacent corrector. If it is possible to neglect betatron phase advance between the quadrupole and the trim then the amount of the compensation to be applied $\delta\alpha_{trim}$ can be found from the formula

$$\delta\alpha_{trim} = \delta\theta\sqrt{\frac{\beta_{quad}}{\beta_{trim}}}$$

The procedure does not require shunts and allows easy automation. The offset of the beam from the quadrupole center can be found from change of the current in the corrector winding which is proportional to the orbit displacement from the magnetic center. Data from magnetic measurements and beam optics can be used for translating current data into the calibrated offsets if needed:

$$\Delta = \frac{\pm\,\delta\alpha_{trim}}{L_{quad}\,\delta K1}\sqrt{\frac{\beta_{trim}}{\beta_{quad}}}$$

Modern orbit feedback and correction systems utilize multiple trims and allow maintaining the global orbit in the storage ring with high accuracy. Therefore, the measurements can be performed when all quadrupoles in the family are varied.

NSLS VUV-ring [3] is a convenient test bench for such method. It has seven quadrupole families. Focusing quadrupoles uvq1, uvq5, and uvq7 as well as defocusing quadrupoles uvq2, uvq4, and uv6 are placed in the straight sections. They are used to control electron beam optics of the Chasman-Green double bend achromat used in the ring. To control dispersion function uvq3 family of focusing quadrupoles is placed in the arcs. The quadrupoles in the straight sections can be used for experiments: the pick-up electrodes are very close to the quadrupoles, which are accompanied by the adjacent vertical and horizontal trims. These correctors have small betatron phase advance from the corresponding quadrupole and have close values of β-functions. The trims are part of the orbit feedback system [4]. uvq4, uvq5, uvq6 and uvq7 families, which are used to compensate lattice distortions due to insertion devices, have two quadrupoles each. uvq1 and uvq2 families have four quadrupoles each. Quadrupoles with odd index are focusing while the ones with even index are defocusing.

First experiments were aimed for the feasibility study and were performed on smaller families having two quads. During the test the orbit feedback system with eight correctors in each plane was on. The main goal was to observe that there is linear dependence of the trims' readbacks on the quadrupole setting and that trims close to the varied quadrupoles are affected.

The results of the try run are shown in Figure 1. The tunes were kept within 0.014 from the initial working point in both planes, and orbit during the measurement was kept within 10 microns. The change of the trims adjacent to the varied quadrupoles was linear, some changes in the other correctors' readbacks were observed as well. However, these changes were significantly smaller and on the noise level.

The following parameters were used for the data analyses:

1) corrector power supply range of 10 A (corresponding to ADC readback of 8192) gives deflection angle 1.55 milliradians at 800 MeV;
2) quadrupole power supply range of 200 A (corresponding to DAC setting of 65535) gives K1=2.63 m^{-2} at 800 MeV;
3) magnetic length of quadrupole is 0.3 m;
4) for the quadrupoles β_x=10.2 m, β_y= 8.0 m;
5) for the trims β_x=7.5 m, β_y=10.8 m.

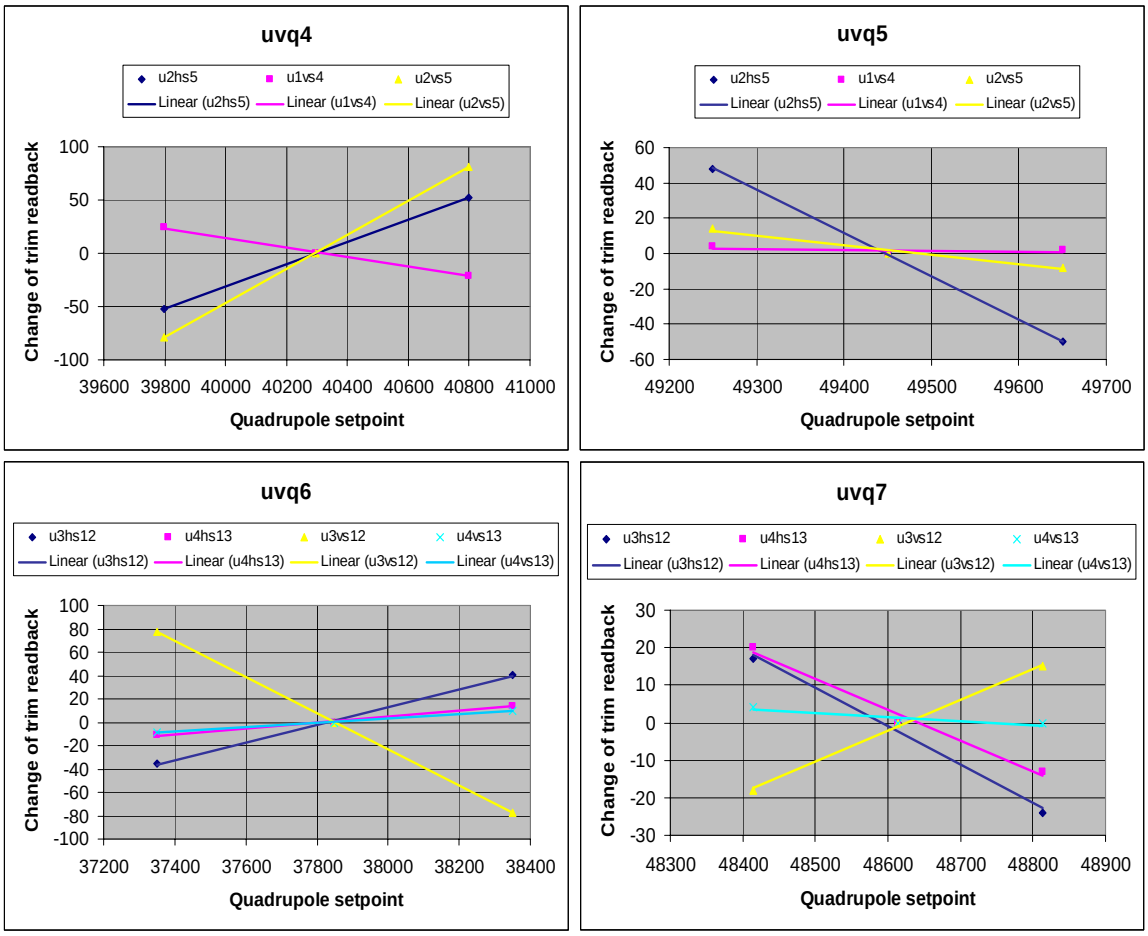

Figure 1. Dependence of trims' readback from quadrupole families' settings with turned on digital feedback.

Table 1. Preliminary data on the orbit offset from the quadrupole centers.

Quadrupole	Horizontal plane		Vertical plane	
	offset, mm	BPM, mm	offset, mm	BPM, mm
Q4a (PUE5)			-0.8	
Q4b (PUE8)	-1.4	-4.5	2.9	1.0
Q5a (PUE6)		-4.4	0.1	1.1
Q5b (PUE7)	-3.3	-3.8	1.0	0.2
Q6a (PUE17)	-1.0		-2.8	
Q6b (PUE20)	-0.3		0.3	
Q7a (PUE18)	-1.4	1.4	-1.5	-2.2
Q7b (PUE19)	-1.1	-1.2	0.2	0.7

The successful attempt has lead to the measurement of all six families on April 29, 2005. Some of the experimental results are shown in Fig. 2. The trim readbacks (ADC code) were obtained by averaging of 1000 samples in order to reduce the readbacks fluctuations caused by the orbit feedback. Standard deviations of the readbacks were σ_h=22 for horizontal plane and σ_v=12 for vertical plane. The obtained orbit offsets from the magnetic centers are shown in Table 2. Large horizontal shift in the injection

straight (uvq1a, uvq1d, uvq2a, and uvq2d) is to move the electron beam orbit away from the injection septum.

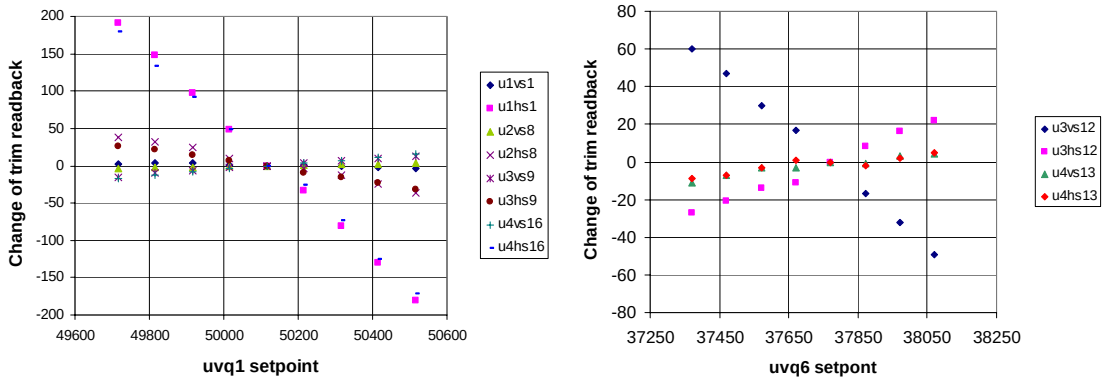

Figure 2. Dependence of the trims' readbacks from two of six quadrupole families' settings with turned on digital feedback.

Table 2. Measured offsets of the electron orbit in the quadrupoles of six families.

Quadrupole	Horizontal plane			Vertical plane		
	offset, mm	BPM, mm	Δ, mm	offset, mm	BPM, mm	Δ, mm
Q1a (PUE01)	-6.19±0.074	-7.20	-1.01	0.12±0.022	0.80	0.68
Q1b (PUE12)	-1.24±0.045	-2.92	-1.69	-0.14±0.009	-0.28	-0.14
Q1c (PUE13)	-0.99±0.020	0.96	1.95	-0.61±0.021	-0.23	0.38
Q1d (PUE24)	-5.79±0.104	-9.28	-3.49	-0.71±0.016	0.09	0.80
Q2a (PUE02)	-2.94±0.080	-5.75	-2.81	0.39±0.023	1.96	1.57
Q2b (PUE11)	-0.39±0.049	-4.03	-3.64	-0.07±0.012	1.03	1.10
Q2c (PUE14)	0.02±0.037	0.35	0.33			
Q2d (PUE23)	-2.32±0.053	-8.81	-6.49	-1.04±0.012	-0.46	0.58
Q4a (PUE05)	-1.29±0.029	-2.78	-1.49	-0.82±0.016	-3.92	-3.1
Q4b (PUE08)	-1.32±0.021	-4.30	-2.98	2.96±0.023	1.03	-1.93
Q5a (PUE06)	-2.63±0.097	-3.65	-1.02	0.18±0.022	0.71	0.53
Q5b (PUE07)	-3.18±0.067	-3.84	-0.66	1.43±0.067	0.02	-1.41
Q6a (PUE17)	-0.97±0.039	-1.29	-0.42	-2.86±0.039	-0.84	-2.02
Q6b (PUE20)	-0.23±0.044	-3.81	-3.58	0.36±0.042	2.31	1.96
Q7a (PUE18)	-1.70±0.078	-2.92	-1.22	-1.33±0.050	-2.08	-0.75
Q7b (PUE19)	-1.40±0.046	-0.92	0.48	-0.02±0.110	0.61	0.63

The numerical simulations were performed to verify method accuracy. The calculations were performed for the horizontal plane. It was assumed that there are offsets of orbit from the magnetic centers of quadrupoles of the uvq1 family are equal to the measured ones using the proposed procedure. Variation of the quadrupole strength with $\delta K1=0.0241\ m^{-2}$ (which value was part of experimental series) gives the following kicks to the electron beam: uvq1a=44.3 µrad, uvq1b=8.9 µrad, uvq1c=7.1 µrad, and uvq1d=41.7 µrad. In order to compensate orbit excursion the calculated trims values are u1hs1=-51.1 µrad, u1hs4=-10.4 µrad, u2hs5=-8.4 µrad, u2hs5=-48.7 µrad. Other four

trims, which are part of the orbit feedback system, are 1 microradian or less. The found compensation provides orbit better then 10 microns. Calculated from the trim values offset differs from the set value by 50 microns at one of the quadrupoles less then 10 microns on three others. The observed trim strength variations were u1hs1=-52.6 μrad, u1hs4=-10.6 μrad, u2hs5=-8.3 μrad, u2hs5=-48.8 μrad, which are in excellent agreement with calculated values.

In order to check the method reproducibility additional measurements were performed on June 10th with uvq1 family. The results are shown in Table 3.

Table 3. Offset of the orbit from the quadrupole magnetic center on June 10, 2005

Quadrupole	Horizontal plane			Vertical plane		
	offset, mm	BPM, mm	Δ, mm	offset, mm	BPM, mm	Δ, mm
Q1a (PUE01)	-6.14±0.208	-7.59	-1.45	-0.44±0.019	0.16	0.60
Q1b (PUE12)	0.19±0.040	-1.69	-1.74	0.06±0.040	-0.10	-0.16
Q1c (PUE13)	0.41±0.061	2.09	1.68	0.01±0.025	0.26	0.25
Q1d (PUE24)	-6.16±0.219	-9.86	-3.70	-1.11±0.062	-0.50	0.61

Table 4 compares the offsets between PUE and quadrupole centers obtained during these two measurements. As one can see there is good agreement between two sets of data. Since VUV ring current had close values during measurements (263 and 239 mA) the difference might be attributed to the seasonal drift. In favor of this assumption is that offsets in the horizontal plane have changed in one direction and amplitudes of shifts are approximately the same with offsets in the vertical plane practically preserved.

Table 4. Comparison of offsets of magnetic centers of quadrupoles vs. BPM centers

Quadrupole	Horizontal plane		Vertical plane	
	April 29	June 10	April 29	June 10
Q1a (PUE01)	-1.01	-1.45	0.67	0.60
Q1b (PUE12)	-1.48	-1.74	-0.14	-0.16
Q1c (PUE13)	1.95	1.68	0.39	0.25
Q1d (PUE24)	-3.49	-3.71	0.80	0.62

CONCLUSION

The proposed method provides accuracy better then 200 microns for centering of the beam position monitors using modulation of the whole quadrupole family.

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