EFFECT OF THE NON-LINEAR MAGNETIC FIELDS ON THE EMITTANCE GROWTH IN THE ATF EXTRACTION LINE*

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Abstract

Since several years, the vertical beam emittance measured in the Extraction Line (EXT) of the Accelerator Test Facility (ATF) at KEK, has been significantly larger than that measured in the Damping Ring (DR) itself. The EXT line that transports the beam to the ATF2 Final Focus beam line has been rebuilt, but the extraction itself remains in most part unchanged, with the extracted beam transported off-axis horizontally in two of the quadrupoles, beyond the linear region for one of them. A few other nearby magnets have also modelled or measured non-linearity. In case of a residual vertical beam displacement, this can result in increased vertical emittance through coupling between the two transverse planes. Tracking studies as well as measurements have been carried out to study this effect and the induced sensitivity of beam optical parameters to the trajectory at injection, in view of deriving tolerances for reproducible and stable operation.

EMITTANCE GROWTH IN THE EXTRACTION LINE OF ATF

One of the main goals of the ATF2 facility, presently under commissioning, is the establishment of the hardware and beam handling technologies pertaining to transverse focusing of the electron beams nearly to 37 nm, reproducibly and in stabilized conditions. For this, beams with the smallest vertical emittances must both be provided by the ATF DR and preserved throughout the different sections of the optical transport.

For several years, the vertical beam emittance measured in the original EXT line, that extracted the beam from the ATF DR, and which at present transports the beam to the ATF2 final focus beam line, has been significantly larger than the emittance measured in the DR itself [1]. One possible contribution that is under study, and is discussed in this paper, is the non-linear magnetic fields in the extraction region experienced by the beam while passing off-axis through magnets of the DR during the extraction process. Simulations including these non-linear fields are presented and compared to observations. Closed orbit bumps in the DR are used to deviate the extraction trajectory and study the effect on the emittance growth.

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Beam Extraction and Diagnostics

The beam is extracted from the DR by means of a first kick, and then passes off-axis through the QM6R and QM7R quadrupoles, nominally at distances of 0.65 and 2.25 cm from their centers, respectively. Then the beam goes through three septum magnets, BS1X, BS2X and BS3X, which complete the extraction.

After the extraction, there is a dispersion suppression section, and the beam then goes through a horizontal dispersion-free zone, where five wire scanners are located in order to allow emittance measurements. At the time of this study, the betatron phase advances between the wire scanners could not be fully optimized to enable reliable emittance reconstruction. A complementary quadrupole scanning technique was also available, but because of practical constraints it could not be used easily during the shifts when trajectory bumps were applied [2]. An alternative method consisted in using an Optical Transition Radiation (OTR) monitor installed just after the septum magnets at a location such that it imaged the beam angular spread out of QM7R with little influence from the beam size in QM7R, thus representing the growth in projected emittance from non-linearities in QM7R quite well. This allowed faster and more reliable results since the measured changes in vertical beam size at this location were well correlated with the emittance growth [3], and because the bumps did not need to be closed in the extraction line during the measurements.

NON-LINEAR MAGNETIC FIELDS IN THE EXTRACTION REGION

In order to quantify the effect of the non-linearity of the magnetic field on the extracted beam, a detailed study of the field maps of the magnets involved in the extraction has been done with the finite element Poisson solver PRIAM [4], from the geometry of these magnets. The obtained field maps have been fitted by a polynomial function in order to get a continuous representation. The results, described in [5], are compatible with those found using the code POISSON [6]. The fit was done by a development in integer series of the complex variable, with complex coefficients, around a reference point:

$$B(x+iy) = B_y + iB_x \sim \sum_{n=0}^{N} a_n (x+iy)^n$$

where B_y and B_x are the magnetic field components in y and x plane, respectively, i is the imaginary number, and a_n is called the $2(n+1)$th multipole field coefficient.

The main contribution to non-linearity in the extraction region comes from the QM7R magnet. At 2.25 cm, where the extracted beam is passing through QM7R, a dipole component appears, the quadrupole component is reduced about 24% compared with the DR value, and a non-negligible sextupolar component also appears. The exact values of the quadrupole and sextupole components (and presumably of higher order components) are very sensitive to the horizontal location where the extraction occurs. The non-linearity in QM6R is negligible, as expected, since the distance from the center of QM6R at which the extracted beam passes is significantly less than the radius of the aperture of the magnet. The extracted beam passes through the BS1X magnet near the edge where a shim is included to help flatten the field, but the obtained multipoles indicate a nearly negligible contribution to the non-linearity. The beam passes through the BS2X and BS3X magnets farther away from the delicate region, where the non-linearity was checked to be small enough to be neglected.

SIMULATIONS INCLUDING NON-LINEAR MAGNETIC FIELDS

Tracking simulations along the EXT line including the non-linear fields of the modelled magnets have been done with the code MAD8 as a function of the bump amplitude, in order to quantify the effect on the beam emittance. The main effects were found to arise from the off-axis trajectory in QM7R, while the downstream optical transport which was modelled did not induce significant growth, in particular where the different wire scanners are located [3].

The non-linearity from QM7R would have negligible effect if the beam were always centered vertically. It however causes significant growth of the effective vertical emittance as soon as the beam passes through vertically off-axis [3, 6]. It increases by about a factor of three for a 1 mm vertical offset, using nominal DR emittances. This growth factor is relatively less if larger input emittances are used, as those measured in the DR during this study.

The ATF orbit is usually stable at the level of about 100 μm, but it could have offsets of a few mm after the extraction, because of systematic orbit distortions in the DR. Simulations show that combined vertical and horizontal displacements cause increased effects on the emittance when going towards the outer part of the quadrupole magnet, while it reduces them as expected when going towards the linear region around its center [3]. Results of these tracking simulations are shown together with the measurements (described in the next section) in Figs. 1 and 2.

EXPERIMENTAL MEASUREMENTS

An experimental measurement program was carried out to check the simulation predictions of the effects of the non-linearity in QM7R [7]. With this purpose, closed bumps in the DR were created to modify the orbit position with respect to the center of QM7R. Measurements of the vertical beam sizes at the OTR monitor were performed as a function of the bump amplitudes. The beam size measured at this location is directly correlated with emittance growth induced in QM7R. In order to discriminate the possible emittance growth due to the non-linear fields in the extraction for variations arising within the DR itself, measurements of stored beam sizes were simultaneously performed with the X-ray Synchrotron Radiation (XSR) monitor in the DR.

Table 1 summarizes the results obtained for the smallest vertical beam sizes measured at the OTR for the different vertical offsets implemented during during each experiment and for the vertical emittances which could be inferred from propagating β and dispersion functions obtained using an optical model representing the magnet settings during the shift. Simulated values with the optical model and including the multipole coefficients computed in [5] are also shown for comparison, using as input DR emittances the measured in each shift [7].

Table 1: Smallest vertical beam sizes measured at the OTR during successive shifts and corresponding emittances calculated from the β-function and dispersion obtained from the model. OTR beam sizes and emittances obtained from simulations. Emittances at the XSR monitor.

	XSR	OTR			
	ϵ_x / ϵ_y (pm·rad)	σ_y (μm)		ϵ_y (pm·rad)	
		Meas	Sim	Meas	Sim
19/12/07	2400 / 36.5	12.8	11.8	40	35
04/03/08	1400 / 41.9	25.9	13.4	155	41
14/05/08	2500 / 44.6	22.6	13.1	127	44
22/05/08	3800 / 27.0	30.8	10.3	228	27
28/05/08	2100 / 22.5	15.1	9.4	40	22

Beam conditions were different in the five data taking periods: while the measurements on the 19th of December 2007 and the 28th of May 2008 gave values which could be compared with the simulation and interpreted in terms of coupling effects from QM7R, during the three other periods in March and May 2008, beam sizes at the OTR monitor were significantly larger and could not be explained in the context of the bump experiments subject of this report. These anomalously large values could be due to anomalous dispersion, to a coupled beam coming from the DR, to a large horizontal displacement of the beam towards the external part of the QM7R magnet, where it is more non-linear, or to some other mechanism. Moreover, the relative increase at the XSR was about as large as at the OTR in these periods.

Figure 1 shows the ratio of the OTR and XSR beam sizes measured on the 19^{th} of December 2007, normalized to the minimum value, as well as results from simulations, as a function of the vertical bump amplitude. The tracking simulations were done with the optical model of the DR and EXT line, and with the input DR emittances the measured during the shift, shown in Table 1.

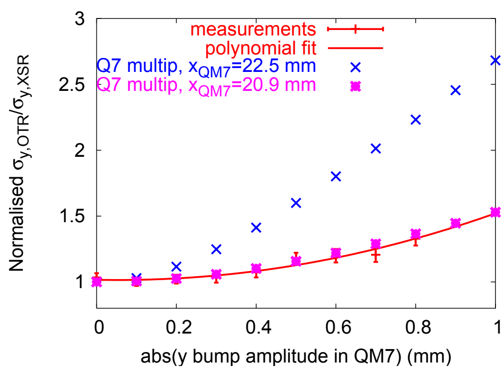

Figure 1: Ratio of the vertical beam sizes at the OTR and at the XSR normalized to the minimum value, measured on the 19^{th} of December 2007, *vs* vertical bump amplitude. Results from simulations for two horizontal extraction positions.

The normalized ratio of the beam sizes at the OTR and at the entrance of the EXT line from simulations are shown for two cases: for the nominal horizontal extracted beam orbit, at 22.5 mm in QM7R, and for the case in which a horizontal bump displaces the beam about 1.6 mm towards the center of the magnet, where the magnitude of the non-linearity decreases, which gives rather similar effect on the emittance growth to the measured one. This shows how sensitive is the non-linearity not only to the vertical extraction position, but also to the horizontal one.

Similar measurements of the beam sizes as a function of the bump amplitude in QM7R were performed on the 28^{th} of May 2008. Figure 2 shows the ratio of the measured OTR and XSR beam sizes, normalized to the minimum value, as well as results from corresponding simulations.

In this case, the measured emittance growth with the vertical bump amplitude is weaker than the measured one on the 19^{th} of December, and for this reason, to obtain a similar emittance growth with the simulations as the measured one, the beam orbit has to be displaced towards the center of the QM7R quadrupole by a bigger amount, 2.7 mm in comparison to 1.6 mm on the 19^{th} of December.

CONCLUSIONS

Tracking simulations including non-linear field errors in the QM7R quadrupole, shared by both the ATF EXT line and its DR, and orbit displacements from the reference orbit in the extraction region predict a significant vertical emittance growth of the extracted beam. The magnitude of the growth also depends on the horizontal displacement, increasing or decreasing in the outer and inner parts of the

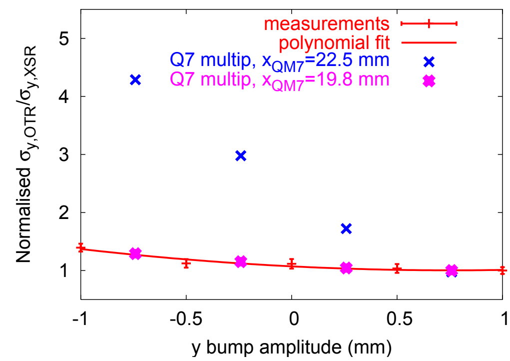

Figure 2: Ratio of the vertical beam sizes at the OTR and at the XSR normalized to the minimum value, measured on the 28^{th} of May 2008, *vs* vertical bump amplitude. Results from simulations for two horizontal extraction positions.

magnet, where the non-linearity is respectively enhanced or reduced.

Measurements using closed orbit bumps in the DR to probe the relation between the extraction trajectory and the emittance growth in the EXT line have been carried out. The results from two data sets show that the non-linear fields in QM7R can explain the emittance growth assuming horizontal displacements through the magnet of a few millimeter, with the beam passing nearer its center. But still there must be another source for the emittance growth, since in three of the data sets the extracted beam was significantly larger than expected even before implementing any bump, with magnitudes which cannot easily be explained by optical effects.

Recently, the QM7R quadrupole was replaced by a similar one with larger aperture, for which magnetic measurements and simulations indicate that non-linear fields are negligible at the beam extraction position.

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