STUDY OF ABNORMAL VERTICAL EMITTANCE GROWTH IN 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, that will transport the electron beam from the ATF Damping Ring (DR) to the future ATF2 Final Focus beam line, is significantly larger than the emittance measured in the DR itself, and there are indications that it grows rapidly with increasing beam intensity. This long-standing problem has motivated studies of possible sources of this anomalous emittance growth. One possible contribution is non-linear magnetic fields in the extraction region experimented by the beam while passing off-axis through magnets of the DR during the extraction process. In this paper, simulations of the emittance growth are presented and compared to observations. These simulations include the effects of predicted non-linear field errors in the shared DR magnets and orbit displacements from the reference orbit in the extraction region. Results of recent measurements using closed orbit bumps to probe the relation between the extraction trajectory and the anomalous emittance growth are also presented.

EMITTANCE GROWTH OF THE EXTRACTED BEAM IN ATF

ATF was built in KEK to create small emittance beams that will be delivered to ATF2, presently under construction. The main goal for the ATF2 project is to establish the hardware and beam handling technologies pertaining to transverse focusing of the electron beams nearly to 40 nm.

For several years, the vertical beam emittances measured in the existing EXT line of the ATF is significantly larger than the emittance measured by a laser wire in the damping ring proper. There are also indications that this emittance growth increases with beam intensity [1]. This long standing problem has motivated studies of possible sources of this anomalous emittance growth, as well as the study of the proper emittance measurement process and reconstruction, which is complicated and could induce some errors in the measurement itself [2]. 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.

Beam Extraction Process

The beam is extracted from the DR by means of a first kick, and then passes off-axis through some magnets centered in the DR. It passes first through the so-called QM6 and QM7 quadrupoles, at a distance of 0.65 and 2.25 cm respectively from the center. Then the beam goes through three septum magnets, BS1X, BS2X and BS3X, which help the extraction. Considering the geometry of these magnets and the distance from the nominal axis of them at which the extracted beam is passing, it can be expected that the main non-linear contribution will be of QM7 when the extracted beam is not on axis vertically [3, 4]. QM7 is an horizontally focusing short magnet of 6 cm length, which means that not only the transverse fields could be affecting the beam, but there could also be some “end” effects of the magnet. A three dimensional study of the magnetic field is also foreseen in order to quantify this effect.

Beam Diagnostics

After the extraction, there is a dispersion supressor section, and the beam then goes through a horizontal dispersion-free zone, where five wire scanners are located in order to allow emittance measurements. Recently an OTR monitor has also been installed just after the septum magnets, located such that it images the beam angular spread out of QM7, with little influence from the beam size in QM7, and hence can represent the growth in projected emittance from coupling in QM7 quite well. After the diagnostic section, the beam is driven to a dump in the existing EXT line. A new extraction line is going to be built to replace the existing one, to drive the beam to ATF2, which is designed in such a way that better phase advances between the wire scanners are expected, which allows to better emittance reconstruction. But the extraction region that comprises the shared magnets with the DR will not be modified.

NON-LINEARITY OF THE MAGNETIC FIELD OF THE QM7 QUADRUPOLE

In order to quantify the effect of the non-linearity of the QM7 magnetic field on the extracted beam, the computation of the magnetic field on a finite mesh has been done with the code PRIAM [5], from the geometry of the magnet. This field map has been fitted by a polynomial function

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with the code MINUIT in order to get a continuous representation [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 By and Bx 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 corresponding multipole coefficients in m^{-n} are:

$$KnL = \frac{L}{B_0\rho_0}\frac{\partial^n B_y}{\partial x^n}$$

where L is the magnet length and $B_0\rho_0$ is the magnetic rigidity. The obtained multipoles are shown in Table 1.

Table 1: Multipole coefficients for QM7 at $x = 0.225$ m and $y = 0.0$ m from the center of the quadrupole from the PRIAM mapping fitted with a polynomial function using MINUIT.

Field Coeff [m]		Multipoles [m^{-n}]	
a_0	4.81·10^{-1}	$K0L$	8.76·10^{-3}
a_1	1.67·10^{1}	$K1L$	3.04·10^{-1}
a_2	-1.28·10^{3}	$K2L$	-4.66·10^{1}
a_3	-1.56·10^{5}	$K3L$	-1.70·10^{4}
a_4	-5.14·10^{6}	$K4L$	-2.22·10^{6}
a_5	3.36·10^{4}	$K5L$	7.34·10^{4}
a_6	4.84	$K6L$	6.34·10^{1}
a_7	2.72	$K7L$	2.50·10^{2}

At 2.25 cm, where the extracted beam is passing through the QM7 quadrupole, a dipole component appears, the quadrupolar component is reduced about 24% compared with the DR value, and a non-negligible sextupolar component also appears. Another field map was obtained with the code POISSON, and a MathCAD-based built-in function was used to fit the calculated field, resulting in reductions of the quadrupolar component of about 20% with respect to the nominal value, and with a sextupolar component slightly smaller [4]. The exact values of K1L and K2L (and presumably of higher order components) are very sensitive to the horizontal location where the extraction occurs.

SIMULATIONS INCLUDING NON-LINEAR FIELDS IN QM7

Tracking simulations along the EXT line including non-linearity of the magnetic field in QM7 have been done in order to quantify the effect on the extracted beam emittance with the code MAD8 [3, 4]. The non-linearity would negligibly affect the beam whilst centered vertically, but becomes important when the beam passes off-axis vertically. In that case, the coupling would increase the projected vertical emittance. The orbit stabilization in ATF achieves levels of about 100 μm, but the beam orbit itself could arrive to QM7 with a displacement of a few mm.

Fig. 1 shows the projected vertical emittance at different locations along the EXT line, as a function of the vertical displacements of the beam in QM7 by means of a simulated vertical bump. When non-linearity of the field is not included in the simulation, there is not significant emittance growth along the EXT line. On the contrary, when the non-linearity of the field is included, the emittance increases about a factor 3 for a beam passing off-axis with 1 mm vertical offset through QM7, with initial geometric emittances of ATF2 nominal ones, $\epsilon_x = 1.2$ nm and $\epsilon_y = 12$ pm, mainly due to the linear coupling, which cannot be effectively corrected in the present EXT line.

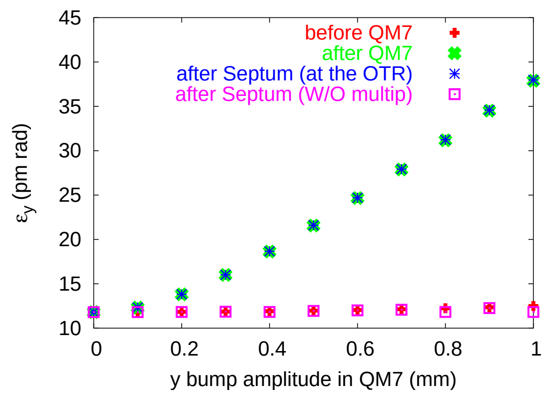

Figure 1: Emittance *vs* vertical bump amplitude in QM7 at different locations of the EXT line, from tracking simulations with and without the multipole coefficients in Table 1.

EXPERIMENTAL WORK FOR EMITTANCE GROWTH STUDIES

An experimental work has been carried out in ATF in order to determine if the predicted effects on the emittance from the non-linearities of QM7 are observed [7]. With this purpose, closed bumps in the DR were created to modify the orbit position with respect to the center of QM7.

Typical emittances measured in the diagnostic section by means of quadrupole scans or multi-wire scans on different dates, are about a factor 3 greater than the measured DR ones. Measurements from 12^{th} March, without any set bump, give respectively, (82±26) pm·rad and (112±13) pm·rad vertical emittances, while the measured one in the DR was 34 pm·rad [2]. But this emittances are bigger than the ones computed from beam size measurements at the OTR after the extraction. A better determination of the β-functions at the OTR may be needed.

Beam size measurements at the OTR as a function of bump amplitudes have been done. The minimum beam size may not corresponds to the configuration without any bump set, because the beam can come with a displacement with respect to the reference orbit. Measurements corresponding to the 7^{th} December, where the measured DR emittances were about a factor 4 greater than the nominals ones, rather agrees with the results obtained by simulations with such an emittances as an input [7]. But there are some discrepancies when smaller emittances were measured in the DR. Fig. 2 shows the measured beam sizes in both DR (XSR monitor) and EXT line (OTR monitor) on 28^{th} May as a function of the bump amplitude. The figure also shows the beam sizes at the OTR obtained by tracking simulations along the extraction region, including multipoles in QM7 on Table 1, with the input emittances corresponding to the measured ones in the DR, $\epsilon_x \sim 2$ nm and $\epsilon_y \sim 20$ pm, for two cases, with and without coupling in the input beam. In the first case a non-coupled beam is used as an input and tracked through the extraction region, and for the second case, a beam is tracked along the DR from the XSR with the DR skew quadrupoles turned on as were in the moment of the measurements (which in the real machine have the function of correcting the coupling from misalignments and errors in the machine), and this results in a coupled beam at the extraction point from the DR.

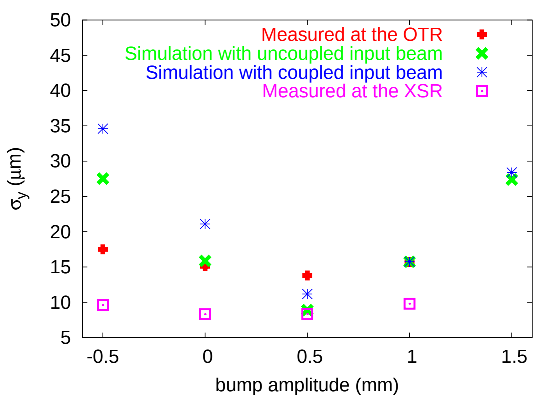

Figure 2: Beam size measurements at the XSR and OTR monitors on 28^{th} May *vs* bump amplitude. Beam sizes at the OTR obtained by tracking simulations are also shown.

Fig. 3 shows the emittance as a function of the bump amplitude at the OTR and XSR computed from the measured beam sizes in Fig. 2 and measured β-functions at the XSR (these are propagated until the OTR). The figure shows as well the vertical projected emittances obtained from tracking simulations with input coupled and uncoupled beams.

The beam sizes at the XSR as a function of the bump-amplitude are rather constant, which indicates that the bump was well closed in the DR. Simulations with an uncoupled input beam predicts slightly small beam sizes for the configuration corresponding to the orbit closer to the center of the magnet. The simulations with the modelled non-linear field for QM7 gives bigger effect on emittance than the measured increase. More studies are needed to understand the dispersions and coupling coming from the DR. The last can be overestimated in the simulation.

CONCLUSIONS

Tracking simulations including non-linear field errors in the QM7 quadrupole, shared by both the ATF EXT line and

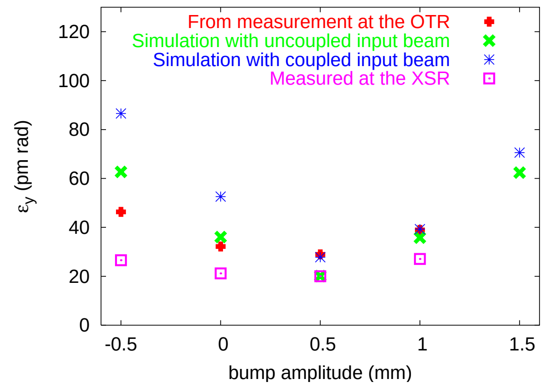

Figure 3: Projected vertical emittances at the OTR and XSR computed from β_y-functions and measured beam sizes, and emittances obtained from tracking simulations.

its DR, and orbit displacements from the reference orbit in the extraction region predict a significant vertical emittance growth of the extracted beam. Recently, 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 show that the non-linear fields in QM7 can explain partially the anomalous emittance growth, but still there must be another source for the emittance growth measured in the diagnostic section of the EXT line.

ACKNOWLEDGMENTS

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