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AG Accelerator Physics - High Brightness Beams

Betatron Tune Knob
Lab Manual
Versuchsbeschreibung zum Fortgeschrittenenpraktikum

Version 1.3

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Contents

1 What you will learn

The goal of the experiment is to derive a method to control the horizontal and vertical tune of the MLS storage ring (betatron tune knob). You will learn basic topics related to the motion of electrons in a storage ring and linear electron beam optics. You will also get in touch with devices to excite and detect coherent oscillations and beam orbit motion. You will also see synchrotron radiation.

2 What you should know

You should be familiar with basic linear electron beam optics [1] and tune measurement and manipulation techniques [2]. Consult [3] for details and parameters of the MLS accelerator complex. You will need the table of MLS parameters in [3] during the experiment. Read and understand the material provided with this script.

3 What to bring with you

Bring a laptop computer or a pocket calculator to compute some parameters during the experiment. It could be useful to implement scripts for the analysis in python or Matlab. With that you can quickly check for any inconsistencies in the data or missing information. If you have an Android smartphone you can download TAPAs [5], the Toolkit for Accelerators on Androids. The app allows back-of-the-envelope kind calculations for typical accelerator physics problems.

4 Motivation

What is the tune? A string instrument like an acoustic guitar needs to be tuned from time to time. A guitar may become *out of tune*, meaning that the tone the guitar is producing is either too high or too low frequency in relation to a chosen reference pitch. This happens with ambient temperature, humidity and other effects. Tuning means here the the process of adjusting the pitch of one or many tones from the guitar to establish typical intervals between these tones.

In a electron storare ring like the MLS the tune is the number of betatron oscillations per revolution. Since the betatron motion is mainly determined by the electron optics the tune is a property of the machine rather than the beam. The exact value of the tune is of great importance in storage rings, where the beam is kept recirculating for many hours while being subjected to all kinds of linear and non-linear forces. At times, small variations of the tune by a few 0.0001 of an integer decide about the well being of the beam. The goal of this project is to characterize the tune and the betatron oscillation in the storage ring and build a tool to tune the accelerator in a determined manner to a chosen reference value, like you would tune your guitar.

5 Background

The material here is mostly drawn from [1, 2, 3, 4]. From [1] read at least Sections 1, 2 (you may omit the part on superconducting magnets), 3, 4, and 5.3. From [2] read the whole article. For the MLS parameters check [3].

The purpose of an electron storage ring like the MLS is to store an electron beam for a long period of time to perform many revolutions (on the order of 10^{11} revolutions, while doing this traveling on the order of 10^{10} km). While stored in the accelerator the electrons emit synchrotron radiation, which can be used for many scientific and technological applications.

5.1 Betatron Motion

In any accelerator there is exactly one path, the design or reference orbit, on which all particles should move. To keep the particles on this reference orbit, restoring forces are needed. If this path is curved like in the MLS storage ring, bending forces from dipole magnets are needed. Since most particles of the beam will deviate from the reference orbit, focusing forces from quadrupole magnets are required. The motion of the particles in the accelerator, under the influence of the restoring forces, can be described by a second order differential equation

$$y''(s) + K(s) \cdot y(s) = 0. \tag{1}$$

The variable y describe the general deviation of a particles trajectory with respect to the design orbit. The horizontal deviations is described with x, the vertical deviation with z. The variable s is the longitudinal coordinate on the reference orbit in the direction of motion (Frenet-Serret coordinate system). The restoring force is linearly proportional to the orbit deviation and to $K(s)$. The equation in Eq. 1 is similar to the equation of motion for a mass m on a spring with spring constant k (Hooke's law), here the spring constant $K(s)$ is piece-wise constant along the orbit, changing its value depending which force, from bending or quadrupole magnet, is acting on the beam. The solution for the amplitude of the mass in Hooke's law describe harmonic oscillatory motion proportional to $\cos(\sqrt{k/m} \cdot t)$, the equation of motion for particles under the influence of restoring forces in an accelerator can be solved with pseudo-harmonic motion described by

$$y(s) = \sqrt{\varepsilon\beta(s)} \cos(\mu(s) - \phi_o), \tag{2}$$

with $\sqrt{\varepsilon\beta(s)}$ describing the amplitude of the motion. The term ε is called the emittance of the beam and is invariant of s. The betafunction $\beta(s)$ and betatron phase advance $\mu(s)$

allow us to assume the motion of the particles without knowing the initial conditions. These transverse oscillations are called betatron oscillations. The betatron oscillation is mainly defined by the arrangement of magnets, in linear beam optics the dipole bending magnets and quadrupole focusing magnets, around the reference orbit. If the restoring force due to the quadrupole magnets is weak, the betafunction $\beta(s)$ will be large and the betatron phase advance $\mu(s)$ for the oscillation will be slow. Converseley if the focusing is strong, then $\beta(s)$ will be small and $\mu(s)$ will be fast. This leads to the conclusion that the rate of change of the phase and betatron oscillation around the ring is equal to the inverse of the oscillation amplitude

$$\frac{d\mu(s)}{ds} = \frac{1}{\beta(s)}. \tag{3}$$

The phase advance per turn L or the number of betatron oscillations per turn around the reference orbit is called the tune Q with

$$Q = \frac{\Delta\mu(s)}{2\pi} = \frac{1}{2\pi}\int_0^L \frac{ds}{\beta(s)}. \tag{4}$$

Since the arrangement of magnets differ between the horizontal (dipoles and quadrupoles) and vertical (only quadrupoles) direction, there is a horizontal tune Q_x and vertical tune Q_z.

5.2 Resonances

In a storage ring like the MLS the beam needs to be stored for many hours. An electron which stays for 8 hours inside the storage ring will perform on the order of 10^{11} betatron oscillations under the influence of the magnetic fields in the MLS travelling roughly 60 times the distance from the sun to earth. There are cases when pertubation terms appear in Eq. 1 which may result in betatron oscillation amplitude instability and growth, under certain circumstances even to beam loss. These pertubation terms may be small ripples in the power supplies, drifts, imperfections in the magnetic lattice (the arrangements of dipoles, quadrupole and other magnets in the ring), or other effects. Some pertubations can lead to a special class of beam instabilities called resonances. Resonances occur when the tunes of the horizontal and vertical plane satisfy

$$m \cdot Q_x + n \cdot Q_z = p \tag{5}$$

where m, n and p are all integers. The order of resonance is defined as the sum of absolute values for m and n. The order determines the strength of the resonance and impact on the beam. The conditions described with Eq. 5 appear when a pertubation acts in synchronism on a particle with it oscillatory motion. Resonances caused by magnetic field imperfections of the magnetic lattice called structural resonances. The resonances with $Q_{x,z} = p$ are driven by magnetic field imperfections in the dipole magnets. If the tune has an integer value, a dipole with a field error will impart a transverse kick on the beam each time the beam passes the field error. The kicks add up and cause an increase in the oscillation amplitude until the electron hits eventually the beam pipe and is lost. Similarly, quadrupoles drive resonances with $2Q_{x,z} = p$ and so on for higher order magnets.

Betatron motion in a circular accelerator occurs in both transverse planes. Pertubations can be present which depend on the betatron amplitude in both planes, these are called coupling resonances. During the Betatron Tune Knob experiment you will investigate properties of 3rd order resonances. In Fig. 1 a tune diagram with resonances up to $p = 3$ order is shown.

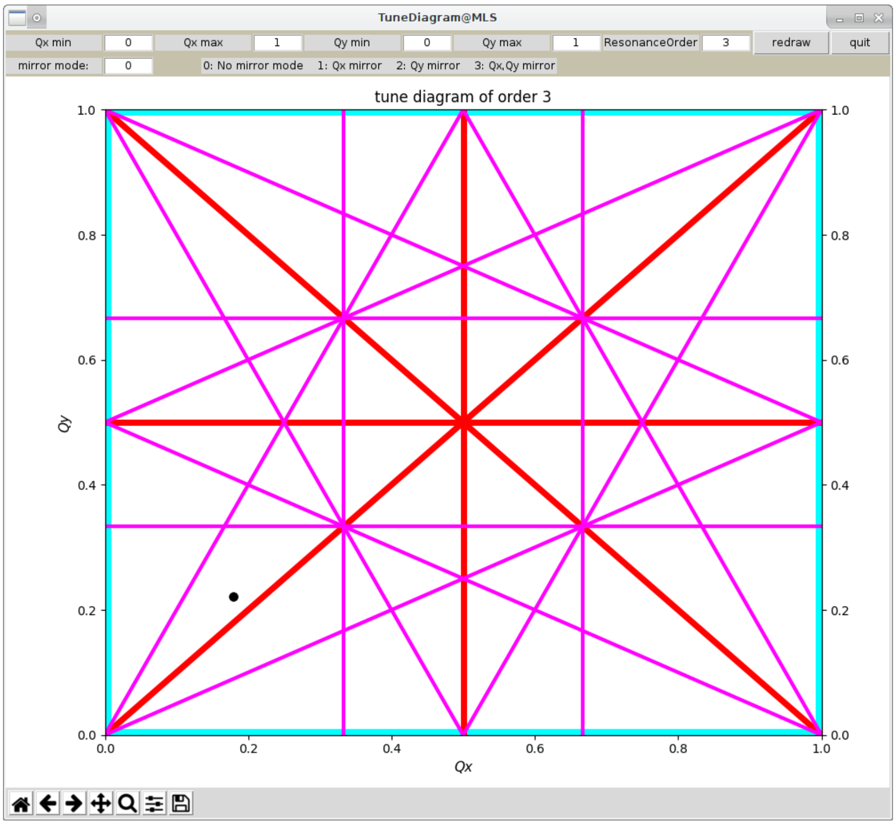

Figure 1: Tune diagram showing the fractional part of the horizontal versus vertical tune. Plotted are resonances up to 3rd order. The black dot marks the working point for the MLS standard optics.

As you can see in the tune diagram it is a challenge to find a working point (that is a vector pointing towards a point in the tune diagramm with given Q_x and Q_z)for the machine operation which is sufficiently far away from any resonances. In addition all resonance lines have a finite thickness called the stop band which further reduces the space for operation without beam loss.

There are many sources of imperfections in the magnetic lattice of the accelerator which can result in a drift of the actual tune. These are gradient errors in the quadrupole magnets, hysteresis effects in magnets during energy ramping and interactions of the electrons in beam with residual gas molecules.

The betatron tune knob we want to develop with this experiment is a multi-knob for the operator of the accelerator to control and the tune.

5.3 Betatron frequencies

We now want to express the tune as the ratio of betatron oscillation to revolution frequency. For this we introduce a smooth approximation, where the betatron oscillation of the particles is approximated with a sinusoidial trajectory in a continuous, uniform focusing field. This is a simplification of Eq. 4. The tune is then given by the mean bending radius R divided by the average betafunction β_n. The phase advance is then simply

$$\mu_{\mathrm{SA}}(s) = \frac{s}{\beta_n} \qquad \text{with} \qquad \beta_n = \frac{R}{Q} \tag{6}$$

The amplitude of the oscillation is then

$$y_{\mathrm{SA}}(s) = \sqrt{\varepsilon\beta_n}\cos\left(Q\frac{s}{R} - \phi_o\right) \tag{7}$$

Introducing the angular frequency of revolution $\omega_o = v/R$ with v the particle's velocity, t time, we can write the general orbit displacement y as a function of time

$$y_{\mathrm{SA}}(t) = \sqrt{\varepsilon\beta_n}\cos\left(Q\omega_o t\right) \tag{8}$$

The betatron frequency is the average rate of change of the phase advance and is denoted by $\omega_\beta = Q\omega_o$ or $f_{x,z} = Q_{x,z} \cdot f_o$. To determine the tune we need to extract the information about the betatron oscillation from measurements of the orbit displacement $y_{\mathrm{SA}}(t)$. Eq. 8 describes a time-dependent oscillation. We will transform this in the following section into a frequency-domain signal.

5.4 Betatron spectrum

In the storage ring, the particles travel inside a metallic tube (see Fig. 2). The particles are accompanied by an electromagnetic field. In the case of relativistic particles these fields are confined due to Lorentz contraction in a thin pancake perpendicular to the direction of motion, with an angular extend of $1/\gamma$, where γ is the ratio of particle energy to the rest energy, resembling a TEM (transverse electro-magnetic) field distribution in a coaxial transmission line. Let us now think of a detector, which can couple to the particle field and delivers a signal proportional to the particle charge and displacement.

Let's call this detector *pickup* and see what signals we can observe in time- and frequency domain.

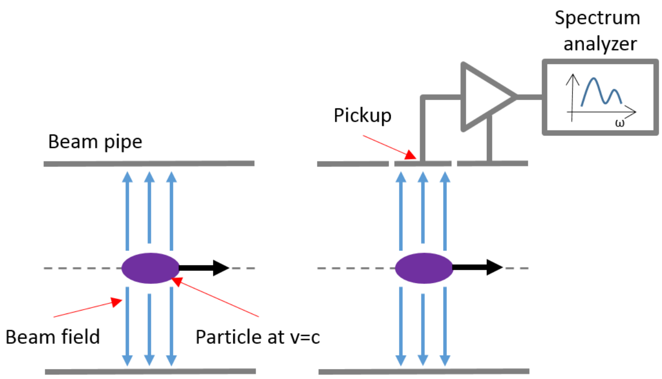

Figure 2: Illustration of a pickup yielding charge and position sensitive information from a particle traveling at speed of light inside a beam pipe.

We now want to derive expressions for the frequency spectra of individual particles in the beam (following Section 2 of [2]). For this we first look at the longitudinal oscillations of a particle while while traveling around the storage ring. Then we include the modulation of the spectrum caused by the transverse (betatron) oscillation of the particle. In Fig. 3 the spectrum in time and frequency domain for these two steps are shown.

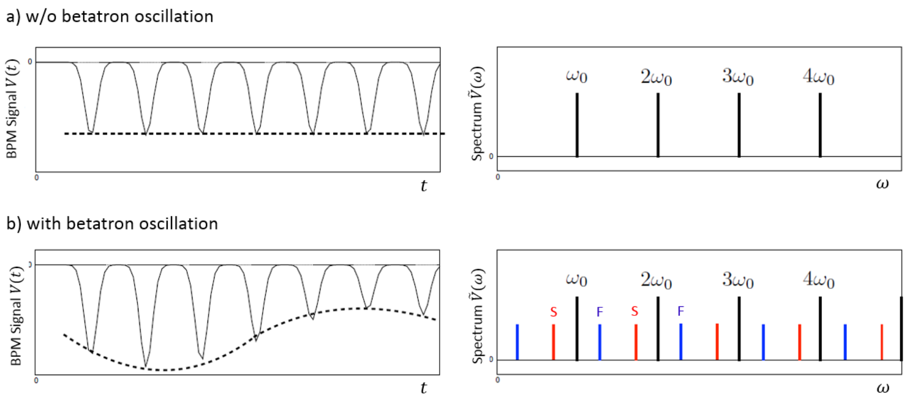

Figure 3: a) shows the time (left plot) and frequency (right plot) domain signal induced by a particle passing a beam pickup. The particle passes the pickup every $1/\omega_o$ and induces for many turns a spectrum of n harmonics. Now add a transverse oscillation to observe the signals in b). Here the amplitude of the time-domain signal is modulated by the transverse oscillation amplitude. Image modified from an original image by T. Uesugi.

In the time domain, the voltage induced at the pickup is

$$V(t) = \sum_{n=0}^{\infty} V_o \delta(t - nT_o) \tag{9}$$

where T_o is the revolution time and V_o is proportional to the particle charge. With betatron oscillations the signal in time-domain is modified to

$$V(t) = \sum_{n=0}^{\infty} (V_o + \Delta V \cos(\omega_\beta t))\delta(t - nT_o), \tag{10}$$

and the amplitude is modulated by the betatron amplitude ΔV, oscillating with the betatron frequency ω_β. The spectrum corresponding to the signal in Eq. 9 is

$$\tilde{V}(\omega) = \omega_o V_o \sum_{n=-\infty}^{+\infty} \delta(\omega - n\omega_o). \tag{11}$$

With betatron oscillations (Eq. 10) the spectrum is modified to

$$\tilde{V}(\omega) = \omega_o V_o \sum_{n=-\infty}^{+\infty} \delta(\omega - n\omega_o) + \frac{\omega_o \Delta V}{2} \sum_{m=-\infty}^{+\infty} (\delta(\omega - (m\omega_o - \omega_\beta)) + \delta(\omega - (m\omega_o + \omega_\beta))) \tag{12}$$

The first sum describes the fundamental frequency of the revolution and its higher harmonics, the second sum the sidebands left to the harmonics (slow waves) and on the right side of the harmonics (fast waves). The sidebands appear at distance $\pm\omega_\beta$ from the revolution frequency.

Note that there is an ambiguity resulting from this as there is no criterion to determine whether the fractional tune q is above or below 0.5., i.e. if a particular mode observed is a fast or a slow wave. A tune with $q = 0.32$ would produce the same spectrum as a tune with $q = 0.68$. Another issues is that a tune of $Q = 1.32$ would produce the same spectrum as a tune of $Q = 2.32$.

The integer part of the tune can be obtained by powering a magnetic corrector and measuring the orbit. After excitation with a dipole field at the location of the corrector the beam centroid will perform betatron oscillations under the influence of the restoring forces of the magnetic lattice. At the MLS several beam position monitors are distributed around the circumference allowing to measure the resulant closed orbit. The number of full periods is the integer part of the tune.

The side with respect to 0.5 can be measured in the following way: Suppose you measure at frequency f_β of a betatron mode just above the n-th harmonic of the revolution frequency f_o. The focusing strength on the plane of interest is then increased and the betatron mode frequency is measured again. If the frequency is higher than before, the observed mode is a fast wave and the fractional tune is $q = (f_\beta/f_o) - n$. If the frequency of the betatron mode is lower, then observed mode is a slow wave and the fractional tune is $q = n + 1 - (f_\beta / f_o)$.

So far we have discussed signals induced into a pickup by a single particle. Inside each bunch in the MLS storage ring some 10^9 particles are mving through the beam pipe. Each of these particles will have the same betatron frequency but with a different phase (ϕ_o in Eq. 8). For the ensemble, our pickup can only detect the charge of the whole bunch and the displacement of the centroid of the bunch. In order to observe the betatron oscillation we need to excite coherent oscillations of the particles inside the bunch (see Fig. 4). This can be done with a device which kicks the beam transversally at each passage, any frequency appearing in the observed betatron spectrum can be resonantly excited.

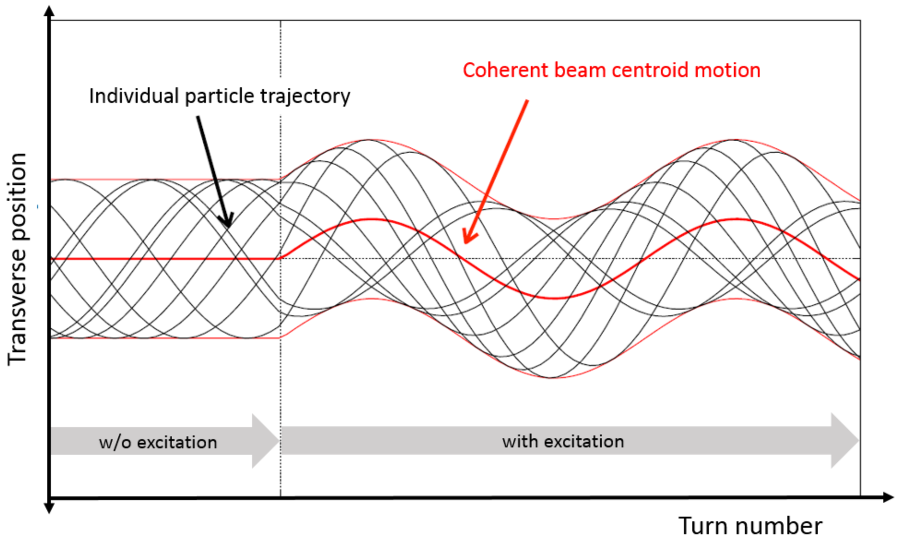

Figure 4: A pickup can only detect the motion of the beam centroid. Coherent oscillations need to be excited to force the beam centroid to perform betatron oscillations. Image modified from an original image by T. Uesugi.

We will use a transverse *kicker* to excite transverse modes by the application of a rapidly time-varying external field. The layout of a kicker is quite similar to a pickup. As with the pickup, we use an electric, magnetic or combination of both fields to act on the beam. An electric field can be generated by applying a voltage between two opposing plates in the beam pipe. At the MLS a stripline kicker (see Section 3.3 of [2]) is used to apply a electro-magnetic field to the beam. The beam can be excited with a fixed frequency tracking the betatron frequency or with a noise generator exciting all harmonics simultaneously. With the excitation the beam centroid motion contains now information about the betatron oscillation. With this the fractional part of the tune can be measured.

5.5 Tune Manipulation

In the previous section we derived a strategy to measure the integer and fractional part of the horizontal and vertical tunes. Now we need a method to control the tune, ideally for each plane individually. Our method will be linked to the previous analysis, the fact that the tune is the number of betatron oscillations per turn and that the betatron ampltiude and phase advance is determined by the focusing strength of the magnetic lattice.

In [1, 2] it is shown that the tune gets shifted by a small amount dQ due to small changes in the focusing strength $dk(s)$ of a quadrupole magnet

$$dQ = \frac{1}{4\pi}\beta(s)dk(s)ds, \tag{13}$$

where β is the value for the betafunction in the quadrupole and ds the length of the quadrupole. A change of dk_F of a horizontally focusing quadrupole QF causes a horizontal tune shift dQ_x of

$$dQ_x = +\frac{1}{4\pi}\beta_x dk_F ds. \tag{14}$$

Summing around the machine leads to

$$dQ_x = +\frac{1}{4\pi}\int \beta_x(s)dk_F(s)ds. \tag{15}$$

There will also be a vertical tune shift. In the vertical plane this quadrupole acts as a defocusing type (QD), $dkds$ is therefore now defocusing and will lead to a vertical tune shift dQ_z of

$$dQ_z = -\frac{1}{4\pi}\int \beta_z(s)dk_D(s)ds \tag{16}$$

Suppose now we take a horizontally defocusing quadrupole and follow the same reasoning. Then we get an overall change in Q_x and Q_z for a QF and QD pair, written in matrix form

$$\begin{pmatrix} dQ_z \\ dQ_x \end{pmatrix} = \frac{1}{4\pi}\begin{pmatrix} +\beta_{zD} & -\beta_{zF} \\ -\beta_{xD} & +\beta_{xF} \end{pmatrix} \cdot \begin{pmatrix} dk_D ds \\ dk_F ds \end{pmatrix} \tag{17}$$

or short

$$\mathbf{dQ} = \hat{\mathbf{A}} \cdot \mathbf{dkds} \qquad \text{with} \qquad \hat{\mathbf{A}} = \frac{1}{4\pi}\begin{pmatrix} +\beta_{zD} & -\beta_{zF} \\ -\beta_{xD} & +\beta_{xF} \end{pmatrix} \tag{18}$$

To compute the required change in quadrupole field need for a desired change in tune, invert the tune transfer matrix $\mathbf{A}$ and solve

$$\mathbf{dkds} = \hat{\mathbf{A}}^{-1} \cdot \mathbf{dQ}. \tag{19}$$

This is the tune knob. Take care with the signs of dk_D and dk_F. As a rule of thumb increasing k_D decreases the horizontal tune and increases the vertical tune, while increasing k_F increases the horizontal tune and decreases the vertical tune.

5.6 Tune Transfer Matrix

The approach we want to follow here is to determine experimentally the values of the tune transfer matrix increments $df_{x,z}$ to quadrupole set current increments $dI_{F,D}$. For this analysis we stay with the description of the betatron motion with the betatron frequencies $f_{x,z}$. We look at the relationship between betatron frequencies and quadrupole increments in a black box way and assume a linear relationship of the kind

$$\begin{pmatrix} df_z \\ df_x \end{pmatrix} = \hat{\mathbf{B}} \cdot \begin{pmatrix} dI_D \\ dI_F \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix} \cdot \begin{pmatrix} dI_D \\ dI_F \end{pmatrix} \tag{20}$$

We can start by setting choosing $dI_D = 1$ A and $dI_F = 0$ A. Then we can compute the first column of $\hat{\mathbf{B}}$ to

$$b_{11} = \frac{df_z}{dI_D} \qquad \text{and} \qquad b_{21} = \frac{df_x}{dI_D}. \tag{21}$$

Now set $dI_D = 0$ A and $dI_F = 1$ A. Then we can compute the second column of $\hat{\mathbf{B}}$ to

$$b_{12} = \frac{df_z}{dI_F} \qquad \text{and} \qquad b_{22} = \frac{df_x}{dI_F}. \tag{22}$$

Invert $\hat{\mathbf{B}}$ to get the desired relationship

$$\begin{pmatrix} dI_D \\ dI_F \end{pmatrix} = \hat{\mathbf{B}}^{-1} \cdot \begin{pmatrix} df_z \\ df_x \end{pmatrix} \tag{23}$$

This is the alternative way to detemine the tune knob. Either way should work for you. The alternative approach should guide you directly to your target and does not need any knowledge of the conversion factors dk/dI.

6 Tune measurement setup

A straightforward way to measure the tune is let the electrons in the beam perform coherent oscillations and detect the beam spectrum with a position sensitive device. A schematic overview of the tune measurement system is shown in Fig. 5.

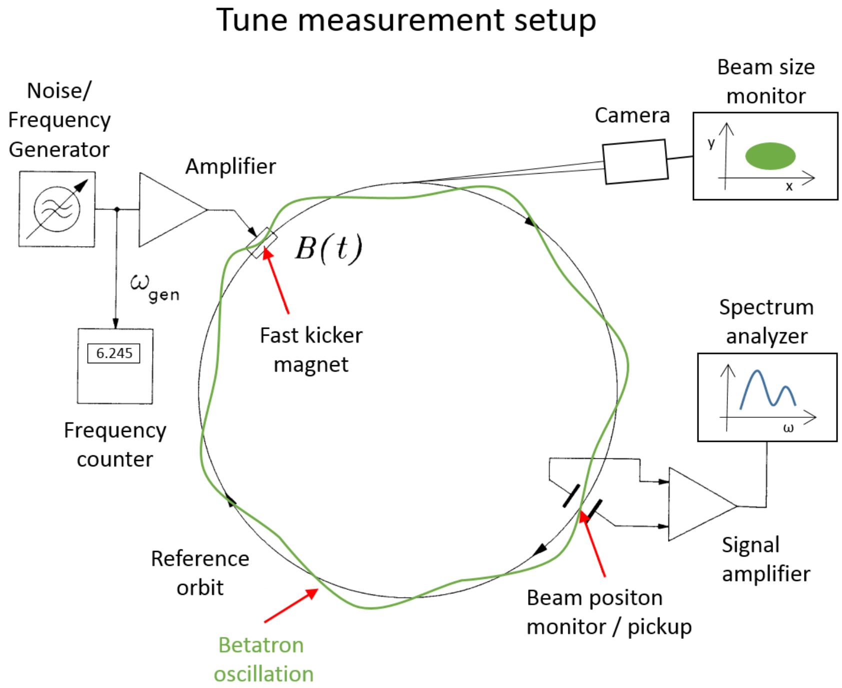

Figure 5: Schematics of the tune measurement system.

The beam traveling on the reference orbit is excited to coherent oscillations with a white noise generator connected to a kicker magnet. The reaction of the beam is monitored in two ways. With a beam position monitor (BPM) beam centroid motions can be analyzed. For this the signal of the BPM is first amplified and then fed into a spectrum analyzer. The change of beam size due to excitation or while traveling close to resonances can be observed with a beam size monitor. The beam size monitor images the radiation emitted by the electrons yielding an image of the actual charge distribution in the electron beam.

7 Setup at the MLS

The experiment is performed at the Metrology Light Source (MLS) of the Physikalisch Technische Bundesanstalt (PTB) here in Berlin-Adlershof. The MLS is an electron storage ring designed and optimized to deliver synchrotron radiation needed for metrology (the science of taking measurements). The accelerator complex is shown in in Fig. 6) and described in [3].

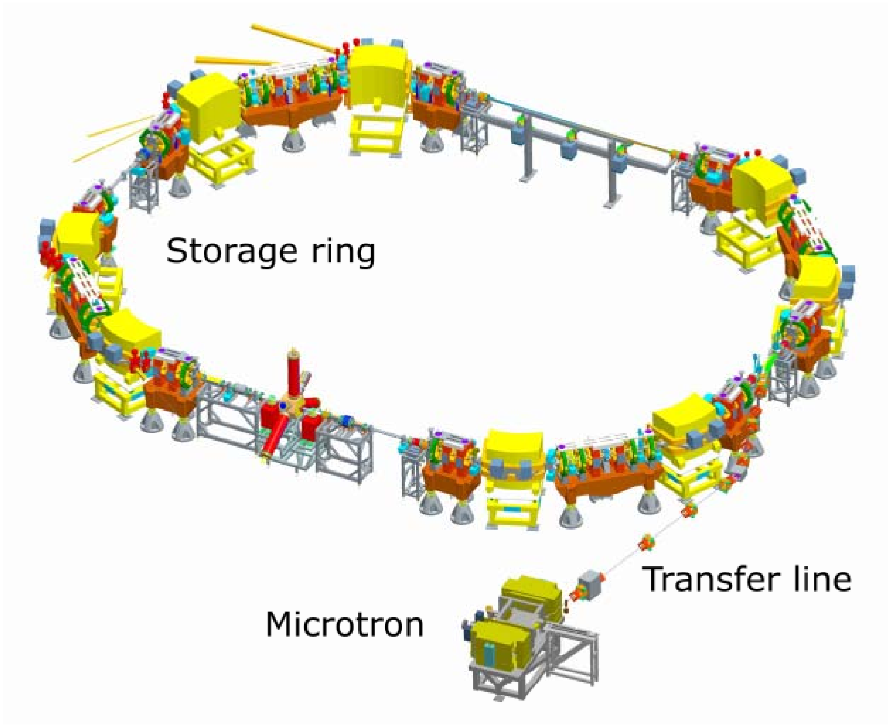

Figure 6: Accelerator complex of the MLS. Image taken from [3].

The accelerator is dedicated to metrology and technical developments in the UV to EUV spectral range as well as on the IR and THz region. For this an electron beam can be stored at beam energies between 50 MeV and 629 MeV and the beam current can be varied between 1 pA (single electron) to 200 mA. At the MLS an electron beam is extracted from a heated cathode and accelerated to 70 keV in the electron gun. From there electrons are injected into a racetrack microtron where the beam energies is increased by several passes to 105 MeV. After this stage the electrons are guided through a transfer line and are finally injected into the storage ring. In the synchrotron the electron beam energy can be set for the desired operation mode.

The magnetic lattice of the MLS storage ring is a double bend achromat (DBA) with four cells. All together 24 individually powered quadrupole magnets provide transverse focusing. For higher order correction and to control the momentum compaction factor, additional 24 sextupoles and four octupoles are located in the magnetic lattice.

During typical user operation the beam current decays from 200 mA to 80 mA in a time interval of 6 h. The current lifetime is here limited by Touchek scattering. Electrons are scattering with each other within a bunch, exchange momenta and may get lost to the acceptance of the machine.

The MLS is a very flexible machine and can be driven in various operation modes. An automated master control program was implemented, that knows all available machine states and all transitions between the states. The beam parameters are relaxed during transitions to maximize the reliability as well as beam current conservation. After the target state is reached beam parameters like momentum compaction factor, beam size or beam emittance are adjusted by optic ramps to fit element settings for the quadrupole and sextupole magnets. Control of the tune, one of the fundamental parameters describing the electron optics, is therefore essential and will be investigated with the betatron tune knob experiment.

8 Instructions

The whole experiment should be done in 3.5 h. Try to reach the checkpoints for each task in the given timeframe. If you think you are lost ask the machine physicist for help.

8.1 Startup

With the help of the machine physicist (1 h): After dumping any remaining beam familiarize yourself with the injection chain for the MLS. Go through all systems starting with the DC gun followed by the Microtron and Transfer Line, and end at the Storage Ring of the MLS. Check the beam transverse spot size with viewscreen monitors (FOMs) along the beampath. Check that the injection septum is running, the injection orbit bump is set so that you can accumulate beam current.

Start then with accumulation and acceleration of an electron from injection energy 105 MeV to the final energy of 629 MeV. Reduce the beam current with appropriate measures to a level the tunes can be easily measured.

8.2 Initial Tune Measurement

With help of the machine physicist (0.5 h): The tune measurement is essentiell to machine operation. Before experiments can be run, the orbit and the tunes need to be checked. The orbit checkout verifies that the beam goes through the center of each magnetic element, the tune checkout verifies the standard optics. For the tune measurement excite the beam to coherent oscillations with the stripline kicker. Use first white noise as excitation source, then switch to a single frequency source to drive the betatron oscillations. What frequencies would you expect for horizontal and vertical betatron oscillation? How can you differentiate between the horizontal and vertical betatron oscillation?

8.3 Integer part of the tune

Determine the integer part of the tune. How many full betatron oscillations per turn does the beam perform with single excitation?

Take a snapshot of the orbit display for your report.

8.4 Fractional part of the tune

Together with the machine physicist (0.5 h): Connect the signal line from the beam pickup to the spectrum analyzer and set it up for a Fourier analysis of the signal and to display the characteristic spectrum with harmonics of the revolution frequency and side bands. Identify the slow and fast waves and the tunes.

Take snapshots of the spectrum analyzer display for your report. Put together a table with the betatron frequencies $f_{x,z}$ and tunes $Q_{x,z}$ on the white board in the control room.

Setup a display in the MLS control system with all relevant parameters, the tune spectrum and strip tools for the set and measured parameters.

8.5 Betafunction measurements

By yourself (0.5 h): Choose two quadrupoles, one from the QF and one from the QD types and measure the betafunctions β_x and β_z for these. Motivate why you chose the particular set. For this change the focusing dk of the quadrupole by current increments dI and record the resulting tune shift $dQ_{x,z}$ as betatron frequency change $df_{x,z}$. For a quick check use the approximation $\beta[\mathrm{m}] = 0.157 \cdot df[\mathrm{kHz}]/dI[\mathrm{A}]$. For the report plot dI versus $df_{x,z}$ and fit a straight line. From the slope compute the value for the average betafunction $\langle \beta_{x,z} \rangle$ in the quadrupole according to Eq. 14. The length of the quadrupoles at the MLS is $ds = 0.2$ m, the conversion factor from quadrupole strength to set current is $dk/dI = 0.064\ \mathrm{m}^{-2}\mathrm{A}^{-1}$.

Now you can setup the betatron tune knob.

8.6 Betatron tune knob

By yourself (1.5 h): Manipulation of a single quadrupole results in a vertical and horizontal tune shift. How do you need to combine different quadrupoles to drive one tune shift only? Find a linear combination of quadrupole magnets to control the horizontal and vertical tune independently. Increase the efficiency of your tune knob by grouping quadrupole magnets. The goal is to implement a horizontal and a vertical tune bump as a control system script. The outcome should be two control sliders, one to drive only the horizontal tune and one only for the vertical tune. Check first that you have all parameters needed to compute numerical values for the tune transfer matrix described in Section 5.6. Invert the tune transfer matrix and compute values for the horizontal ($dQ_x = 0.01$, $dQ_z = 0$) and vertical ($dQ_z = 0.01$, $dQ_x = 0$) tune bumps. What set quadrupole current increments $dI_{F,D}$ are required for the two tune knobs?

Check now the linearity of your tune bumps. Drive your tune bump slider and record the actual tune shift in the desired and other plane. Plot measured versus set values for the tune, fit a straight line and check when the straight line differs by more than 1% from data values. From the plot also give a value for the tune leakage, when and by how much does the other tune change.

Identify in the tune diagram the closest resonances of third order and try to cross the resonance with your tune bumps. Move the beam close to horizontal and vertical resonances as well as close to difference and sum resonances. What happens to the beam when the tune approaches those resonances? Discuss your observations. Near difference resonances, the coupling between the horizontal and vertical plane transfers energy from horizontal to vertical motion and thus the amplitude in the vertical plane increases periodically.

8.7 Close out

Finish up your measurements and check that you have all data with you. Ask the machine physicist to help you collect the data from the control system data archiver. Take some screenshots illustrating your work. Clean up your working place for the next group.

9 Deliverables for the report

The written report should be submitted two weeks after the experiment. It should follow the general recommendations for the F-Praktikum.

The report should contain a brief introduction and motivation for the betatron tune knob. In the introduction you should introduce all formulas you deploy later on in the analysis of the measurements. The introduction should not be longer than one page. The motivation should be clearly stated: Why is the betatron tune knob important? In the following section you should briefly describe the accelerator, your methods and the tools you are using for the experiment. This section should be on the order of two pages long. Discuss now the results from the initial tune measurements (integer and fractional part of the tune), betafunction measurement and measurement of the tune transfer matrix to setup the tune knob. Write up what you did and what you found. Discuss your results and formulate take home messages. Devote on the order of four pages on this. The last result section discusses the action of the tune knob while driving the working point in the tune space in the vincitiy or resonances. This section may add half to one page to your report. Finish the report with a summary and references (half a page). In total your report could have on the order of eight pages.

References

[1] J. Rossbach and P. Schmüser, Basic course on accelerator optics, CERN Accelerator School, 5th General Accelerator Physics Course, CERN-94-01-V1, available at https://cas.web.cern.ch, pp. 17-88

[2] M. Serio, Tune measurements, CERN Accelerator School, Introduction to Accelerator Physics, CERN-91-04, available at https://cas.web.cern.ch, pp. 136-160

[3] M. Ries, Nonlinear momemtum compaction and coherent synchrotron radiation at the Metrology Light Source, PhD thesis, HU Berlin, 2014-05-26, DOI: 10.18452/16979, pp. 3-7

[4] S. Jena, et al., Stabilization of betatron tune in Indus-2 storage ring, arXiv:1307.4512 [physics.acc-ph]

[5] M. Borland, TAPAs, The Accelerator Physics Toolkit for Androids, see Google Play Store