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Measurement Topics for the Commissioning of the ELETTRA Storage Ring
Part I: The First Months

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1. Introduction

Under the term "Commissioning" we mean all the necessary actions for checking and optimizing a machine in order to meet its specifications.

It is then evident that for an effective commissioning one must know in advance how the equipment should be checked, what should be measured, how it should be measured and with what operational strategy. In brief one must answer, well before the commissioning starts the questions: "what", "how", "with what".

The scope of this report is to provide the link between the information that will be obtained from the various instruments during the first stages of the commissioning and its use in extracting the physics i.e. the "how" question. To this extend it is also a guide to the information needed i.e. the "what" question. For complementarity however in the next subsection a standard commissioning strategy is briefly mentioned.

The required hardware i.e. the "with what" question, is also reported when necessary without nevertheless going into great detail.

Although this report is written to facilitate the commissioning of the ELETTRA storage ring the procedures described may also be used in other rings, not necessarily similar to ELETTRA. It is true that various machines have different problems however the commissioning procedure is more or less the same in all of them.

1.1 Standard Commissioning Strategy

Formally the commissioning may be divided into five steps that in practice are not completely separated from each other; however this division can be helpful in setting priorities and thus providing a logical framework of action.

1) Before starting up the equipments should be thoroughly checked and should fulfil preset initial conditions depending upon the commissioning stage. As an example the vacuum pressure or the alignment requirements needed at the beginning may not be that required during normal operation. During this phase the magnets and the fast magnets should be checked, their polarity and their interlock should be tested. Some diagnostics should be already available including the most of the beam position

monitors. The rf cavities should be ready for operation and able to compensate the alignment errors.

2) Starting-up with simple conditions. Some application programs should be available and already functioning. This includes programs measuring lattice characteristics, programs controlling the BPMs and steerers, orbit correction, rf control, set the injection elements, tune the dipoles and quadrupoles and monitor the vacuum. For this first control one may work with very low beam intensities and part of this work is to make the so called "first turn steering", i.e. to achieve some beam revolutions. This achievement does not necessarily prove that the machine has the design optic but it is rather an additional equipment check (e.g. vacuum chamber continuity) and need not be performed with rf on. With the sextupoles off a larger dynamic aperture is available. Check for ripples in the various power supplies.
During the first turn steering one tunes the septum and adjusts the value of the currents in the ring dipoles and quadrupoles. On axis injection, so that induced coherent betatron oscillations are avoided, may also be useful. More about injection in section 15.
It is very important that the magnets are cycled before setting their final current -at all stages-due to magnetic hysteresis effects.

3) When some revolutions are achieved one may start checking the optics. This includes estimating and correcting the uncertainty on the quadrupole magnet current settings and applying the orbit correction procedures. Measurements of the betatron phase advance is a convenient tool for checking the focusing.
Due to synchrotron radiation losses, without rf the beam will move 0.5 mm per turn towards the inner wall of the chamber. This means that one may observe as many as 80 revolutions before the beam hits the wall. With the rf off the BPMs will still deliver a signal, since for debunching at least 150 10^3 revolutions of the injected pulse is needed.
Switching on the rf one may attempt to store the beam. This includes the rf frequency optimization via estimation of the off-momentum. When a stored beam with some lifetime is achieved one may try to check the BPM readings, measure the beam position and perform some closed orbit corrections. Finally the sextupoles are switched on. Check for ripples in the various power supplies.
At this stage the beam intensity need not be (and usually it is not) high but it should be monitored in order to provide information for the working point.

4) At this stage one measures and optimizes further the optic and studies the impact of the insertion device(s) to the optic. Measurements of the tunes, betatron functions, chromaticity, dispersion and injection energy should be at this stage fully enabled. Other measurements like beam lifetime, beam current and dimensions - emittance, energy spread at injection, momentum acceptance and dynamic aperture can also be performed towards the end of this stage. Some investigation of intensity dependent effects may be also started. All these measurements should be preferably repeated as a function of the insertion device(s) gap size.
After adjusting the values towards the specified ones (e.g. tune adjustment), one usually starts again from the second step. However here all the systems of the machine should be on.

5) This last stage usually comes later and is that of intensity optimization and machine experiments in order to understand the behaviour of the machine. This includes measurements of the beam lifetime as a function of various variables like pressure, gas scattering, Touschek scattering etc. Here one usually studies the intensity dependent effects and measures the ring impedance. (The measurements during this stage will be described in a forthcoming report consisting the second part of the present work.)
It is a standard practice that after machine shut downs for whatever reasons one should start again from first step. Usually one is forced by the machine itself to start again this way.

1.2 Instrumentation Needed

To make all these measurements in the ELETTRA storage ring we have at our disposal the following instrumentation:

a) 96 position monitors (BPM);
b) 1 DC current transformer (DCCT);
c) 1 synchrotron radiation light monitor (SLM);
d) stripline electrodes (SE);
e) 1 horizontal and 2+1 vertical scrapers;
f) 7 fluorescent screens (FS);
g) 2 annular electrodes for duplicating the beam intensity information and;
h) many "hardware" signal output jacks to be connected at will to oscilloscopes.

In table 1 (see the Appendix) and in priority order it is listed what should be measured and the proposed instrumentation.

Since the scope of the report is to extract the physics from the instrumentation it is important to know what signals the various instruments deliver on an oscilloscope and this will be shown in every section.

In general the various types of signals (noting that all the above mentioned instrumentation is generically named "beam sensors") may be classified:

a) by the type of the method used to "sense" the signal i.e. electric induction sensing the charge, magnetic induction (current), electromagnetic , destructive etc.
b) by the moment of the measured beam distribution i.e. monopole moment (beam current), dipole moment (beam position) etc.

Accordingly to measure the dipole moment (beam position) one may use an electric pickup monitor (BPM), a magnetic pickup monitor (DCCT) -which however is more useful for monopole (current) measurements - or an electromagnetic pickup monitor (stripline).

Finally for a better understanding at the end of some sections we present numerical examples. In these examples we use realistic numbers i.e. numbers that one expects to measure during the commissioning of the ELETTRA storage ring.

2. Orbit Check and Correction

Checking the orbit is the first and very important step in the commissioning. For ELETTRA the check will be mainly accomplished using beam position monitors (BPM) that reveal the beam orbit.

One may associate every point of the beam with a triplet (s,x,y). If s represents the longitudinal distance along the design trajectory of the ring (measured from an arbitrary initial point) and x, (y) represent the horizontal (vertical) displacement, the set of all these triplets defines the beam orbit.

If we represent the radial dimension with r (= x or y) one may generally write:

$$r(s) = [\, r_{co}(s) + D_r(s)\, \delta_0 \,] + r_\beta(s) \qquad (2.1)$$

where $D_r(s)$ is the dispersion function and δ_0 is the momentum deviation from the design orbit. The term inside the square brackets is the periodic part of the trajectory and the non-periodic term represents the betatron motion which for both planes it can be expressed, in terms of the usual Twiss parameters a, β, μ, as:

$$r_\beta(s) = a_r \sqrt{\beta_r(s)} \cos [\, \mu_r(s) + \mu_r(0) \,] \tag{2.2}$$

The $r_{co}(s)$ represents the (imperfect) closed orbit due to field errors (e.g. including misalignments, correction magnets etc.). Then, for instance, for N kicks θ_i around the ring (e.g. from orbit correctors) the vertical displacement (on-momentum imperfect closed orbit) will be given by:

$$y_{co}(s) = \frac{\sqrt{\beta_y(s)}}{2 \sin(\pi Q_y)} \sum_{i=1}^{N} \theta_i \sqrt{\beta_y^i(s)} \cos [\, \pi Q_y - |\, \mu_y(s) - \mu_y^i(s) \,|\,] \tag{2.3}$$

The term $D_r(s)\ \delta_0$ takes care of the off-momentum effects. More about these may be found in General Bibliography reference 2. (e.g. see article by J-P. Koutchouk).

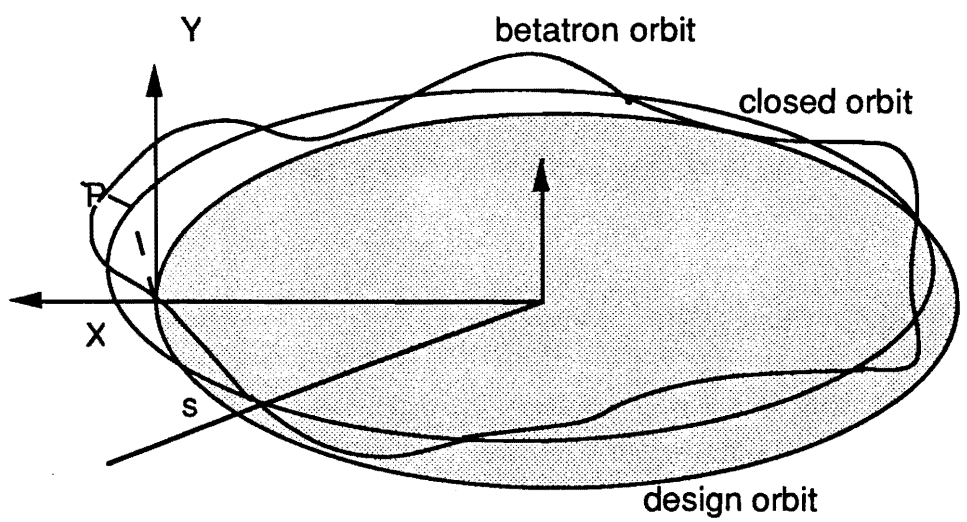


Figure 1. (not to scale)

The number of betatron oscillations along the ring circumference (which must not be an integer or semi integer) is the betatron tune $Q_{x,y}$ (= betatron frequency/revolution frequency) and consists of two parts, an integer part and a fractional part.

Also the longitudinal position of a particle in the beam may be written as $s = s_0 + \Delta s$ where s_0 is the position of a (fictitious) synchronous in energy particle at the bunch center and Δs refers to the longitudinal displacement of any other particle in the bunch relative to the synchronous particle. It turns out that Δs is described by yet another harmonic motion in order to ensure phase stability (i.e. the bunch remains a bunch). The number of energy oscillations along the ring circumference is the synchrotron tune Q_s (= synchrotron frequency / revolution frequency).

In short, a particle inside a bunch is executing a rather complicated motion. There is a fictitious point identified with the centre of the bunch that is moving along the closed orbit. Then a particle P being displaced (Δs, Δr) from it will execute a non periodic harmonic motion in all three directions around the bunch center (see figure 1).

2.1 BPMs and their Signal Identification

These monitors measure the coordinates of the bunched beam centroid relative to the design orbit (usually the middle of the vacuum chamber cross section) at a fixed number of locations along the circumference. The set of these coordinates is commonly referred to as the orbit.

At each BPM station there will be located 4 electrodes, therefore one can measure transverse as well as longitudinal position, in the rectangular arrangement. Due to their high number (96) the signal will be transmitted via multiplexing.

The BPMs can measure at rather low intensities producing a signal whose intensity is proportional to the transverse angle subtended from the beam and roughly proportional to the derivative of the charge distribution.

The BPMs assist and facilitate many measurements, but they have to be thoroughly checked (e.g. their polarity) at the very beginning of commissioning so that one is sure that they measure indeed what one thinks they should measure.

For large orbit deviations the button BPM is a non-linear device and this should not be forgotten at the initial stages of commissioning (i.e. for large deviations the frequency contains of the measured orbit is amplitude depended).

Two quantities characterize a BPM, the resolution and the accuracy. The resolution is a measure of the smallest resolvable beam motion (typical modern resolutions 10 μm)

whereas the accuracy defines the error between the measured beam position and the actual beam position relative to an absolute position reference usually given by the quadrupoles alignment marks (accuracies of 0.1 mm are needed for ELETTRA).

The delivered signal is usually plotted in a two dimensional graph where the vertical axis measures the beam's deviation from the monitors center. The horizontal axis, depending upon the application, is usually the ring circumference and therefore deviation against the monitor position is plotted. Usually two such graphs are provided: one for the horizontal and the other for the vertical beam deviations. A typical picture is shown in figure 2:

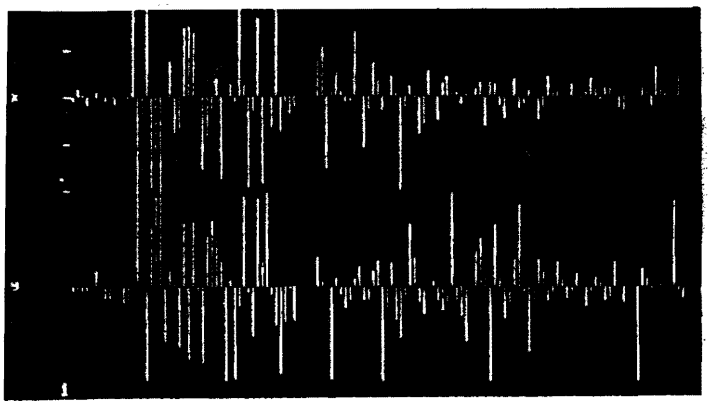


Figure 2.

The BPM system of the ELETTRA ring integrates the beam position over 1200 turns (integration time ~ 1 ms) therefore turn by turn representation during normal operation can not be automatic and may be obtained only for a few BPMs at a time by using the unprocessed signal (i.e. before integration) on an oscilloscope.

The BPMs may be used as a diagnostics instrument for injection studies, for a few turn studies and for a fully stored beam.

2.2 Using the BPMs with an Injected Beam

The BPMs may be used for the setting of the dipole current (step 2 of subsection 1.1). After cycling the dipoles one sets the corresponding to the energy theoretical current. With the quadrupoles off (no focusing) the injected particles will not survive for more than maybe a few achromats and if the reading of the last monitor in the injection cell is zero the value of the current is correct, else it must be changed until the reading is zero. This current will correspond to a beam path with a momentum deviation uncertainty of 1% coming from the linac and fine adjustment is needed. This may be achieved by using the readings of the 3 first monitors after the dipole that are in the dispersion region. One has to adjust the current in such a way that the sum of the squared differences between the BPM readings and the theoretical dispersive orbit (off-momentum, see subsection 1.1) becomes a minimum. If possible more achromats should be considered for more accuracy.

In a similar way the errors of the vertical injection angle may be corrected. Here one minimizes the sum of the squared differences between the vertical BPM readings and the product of the vertical angle error times the needed vertical position at the BPMs. Two appropriate vertical correctors in the cell may then be used for the indicated corrections.

The BPMs may be used for the first turn transmission. In doing this one tries to transport the beam step by step by minimizing the horizontal and vertical orbit deviations shown in the monitors by operating the correction coils (steerers) in order to achieve one revolution. During this process one should also check for wrong polarities. At ELETTRA a program has been already written [2.1] for first turn steering that performs at the same time a BPM and magnet polarity check.

Once the first turn steering has been completed, a harmonic analysis of the steerer strengths will reveal the off-momentum δ_0. This is due the the fact that by correcting the closed orbit (i.e. r(s)=0) one is forced to apply kicks that are defined by eqs. (2.2) and (2.3) resembling thus a sinusoidal form. Since the dispersion is almost constant in the arcs and zero at the straight sections, from eq. (2.1) one sees that the compensation of the off-momentum term is achieved by a resultant constant kick which will appear in the strength harmonic analysis as the 0th order term.

Although the BPM resolution for an injected current of 20 mA is of the order of 0.2 mm [2.4], four linac pulses are needed to obtain the beam position. This limitation may decrease the accuracy of the monitors if the linac energy is not stable.

Actual beam position may be also indicated by using the fluorescent screens (see also section 12) and although this method is destructive for the beam it is (mainly at the beginning) very useful. The fluorescent screen after the injection septum may be also used for the injection optimization.

2.3 Using the BPMs in a few Turn Beam

To obtain some turns the quadrupoles should be turned on (and cycled). Setting the nominal currents in the quadrupoles there is always a current uncertainty which changes the focusing and therefore also the phase. The focusing may be checked by measuring the phase advance between the achromats with the BPMs. Measuring only the tune is not sufficient here (if at all possible at this stage) because one may have the right tune with the wrong optic. However the tune may be found adding the achromat to achromat phase advance.

The tune nevertheless is useful in adjusting the quadrupole currents. One draws a graph of vertical and horizontal tunes versus $\Delta I/I$ error of the quadrupole currents. Changing the current one should find the value at which the tune graphs meet (at different scales) and the applied correction to all quadrupole families then it should be $-\Delta I/I$. After adjusting the quadrupoles one must optimize again the orbit.

The BPM may be also used to ensure on-axis injection which is usually used in order to eliminate the coherent betatron oscillation so that orbit distortions and alignment errors may be easier studied. The resolution of the BPMs should be sufficient; however its energy shift due to synchrotron radiation and the betatron phase shift in case of non corrected chromaticities may cause further loss of resolution for the horizontal readings.

Provided that there are some beam revolutions one may perform fast closed orbit measurements. Indicating with X the perfect closed orbit (term inside the square brackets in eq. (2.1)) the BPM will measure $r(s) = X(s) + r_\beta(s)$ with $r_\beta(s)$ given from eq. (2.2).

If the trajectory is observed at a certain point every turn i.e. for $s = s_0 + n\,L$, where L is the length of the ring circumference and n is the number of turns, the observed orbit displacements will be:

$$r_n = X + \alpha\sqrt{\beta_0}\cos(2\pi\, n\, Q + \phi_0) \tag{2.4}$$

From eq. (2.4) one sees that four turns (i.e. n, n+1, n+2, n+3) are sufficient to eliminate the Twiss parameters and find both tune and closed orbit:

$$\cos \mu = \frac{1}{2} \frac{r_{n+1} - r_n + r_{n+3} - r_{n+2}}{r_{n+2} - r_{n+1}} \tag{2.5}$$

where $\mu = 2 \pi Q$ and

$$X = \frac{1}{4 \sin^2 (\mu / 2)} \left(r_{n+2} + r_n - 2 r_{n+1} \cos \mu\right) \tag{2.6}$$

This technique may be very useful at the initial stages of commissioning. The processing of the BPM signals in ELETTRA does not allow a turn by turn measurement. However the latter may be possible for a small number of BPMs (e.g. 12) by using the unprocessed signal and an oscilloscope equiped with a memory function.

2.4 Using the BPMs with a Stored Beam

To get a stored beam the rf must be turned on and the frequency (by checking the off momentum) and voltage should be optimized for maximal beam survival. Much more can be done with the rf frequency (phase) than with the voltage.

During injection there may occur a timing error and/or the beam to have an energy error. In the first case the beam will not be injected in the middle of the bucket and for a time as long as the radiation damping time, losses may occur. If the closed orbit is wrong (misalignment errors, energy error etc.) the bucket acceptance will decrease. Losses then may also be due to via synchrotron oscillations induced energy oscillations producing a tune shift large enough so that betatron resonance lines are crossed. If the timing is wrong one must fine tune the injection timing (e.g. rf-phase) by looking at the longitudinal signal from a pick-up and if the injected beam energy is wrong or the closed orbit error very large one should optimize the rf frequency (In ELETTRA 1 mm of error in the ring circumference corresponds to 2 kHz rf frequency shift). However if these errors are small the cavity will automatically compensate them. Correction is achieved by looking at the coherent tune shift signal from a pick-up on a oscilloscope and changing the phase.

Next closed orbit corrections are performed while checking again for faulty BPM readings. The final step is to power the sextupoles (after cycling them) while having a closed orbit corrected to maybe less than 1 mm.

One might ask by looking at eq. (2.1) which term a BPM measures. It comes out that in principle one can obtain all those terms.

The closed orbit (the terms inside the square brackets of eq. (2.1)) may be extracted if one averages each BPM data over many (n) turns. This is due to the fact that although the individual particles in the beam are executing betatron oscillations their centroid moves along the closed orbit. As it has been already mentioned the electronic signal processing of the ELETTRA BPMs is doing exactly this i.e. no betatron oscillations may be seen with the standard operational BPM mode.

To extract the betatron oscillation one must subtract the closed orbit from the measured orbit. This may be achieved in ELETTRA by sampling a very small number of revolutions i.e. before the betatron motion is averaged out and subtract it from a file with the closed orbit that has been obtained shortly before.

One may extract the average orbit due to momentum deviation δ_0 by averaging many closed orbit data, since the first term in square brackets in eq. (2.1) tends to vanish if it is centered. However the momentum deviation may be also obtained using other methods.

The imperfect closed orbit (eq. (2.3)) is found by subtracting the energy dependent component from the closed orbit.

2.5 Correcting the Orbit

In case that the measurements reveal that the orbit is not the desired one or at the worst case if there is no orbit at all one should try and correct it. Orbit correction is the most repeated procedure over the accelerator lifetime (and not just during commissioning) simply because the machine moves due to vibrations.

During correction one tries first to establish a closed orbit (referred to also as the reference orbit) that agrees most closely with that defined by the centers of the quadrupoles and sextupoles and to do this, one may use all the magnetic elements of the ring (mainly quadrupoles and steerers).

To check if the beam is passing through the center of a quadrupole field one may use the fact that the quadrupole will not steer unless the beam is off center. However this implies the existence of independent power supplies. In ELETTRA there are 3 pairs of independently powered quadrupoles in each achromat.

Once a closed orbit has been achieved one then may start using the steerers in order to improve it. Improvement means that the signal derived from each individual BPM is minimized (global correction) but in some cases one may on purpose correct locally (e.g. to match with a beam line) and the procedure is called local correction. In ELETTRA both methods will be used by adapting the CERN package COCU to our needs [2.5].

To briefly illustrate the "essence" of the correction methods we show a very simple method for global correction, the so called " the most effective corrector". This is an iterative procedure which seeks to minimize the sum of the squares of the BPM readings.

Assume that there are M position monitors measuring the y_i for i=1,..., M orbit displacements vector. The change of this vector due to j^{th} kick θ_j is given via eq. (2.3), which may be alternatively written as $\delta y_i = A_{ij}\,\theta_j$.

Defining $F_1 = \Sigma\,(y_i)^2$, $F_2 = \Sigma\,(y_i + \delta y_i)^2$ and $\Delta = F_1 - F_2$ one tries to find the most efficient θ_j that maximizes Δ and keeps it positive, so that we have a reduction of the displacement vector with the highest effectivity.

This means that $d\Delta/d\theta_j = 0$ with $d^2\Delta/d\theta_j^2 < 0$ and $\Delta > 0$. It is a simple matter to prove that the above conditions are satisfied if $\theta_j = -\,\Sigma\,A_{ij}y_i/\,\Sigma\,(A_{ij})^2$ and the induced corresponding change of the sum of the squares is $\Delta_j = (\Sigma\,A_{ij}y_i)^2\,/\,\Sigma\,(A_{ij})^2$. For each steerer j, Δ_j is calculated and the largest value is found. The steerer that corresponds to that largest value of change e.g. Δ_k is then powered accordingly i.e. the correction kick is changed by θ_k the process being iterative and fast converging.

3. Betatron Tune Measurements

The betatron tune is basically a property of the machine rather than the beam, although it may depend on the beam intensity. Its measurement is a major tool for the optimization of injection, current intensity and general performance of the machine, whereas in the commissioning phase it is used to check and correct the lattice.

The BPMs may be used to give the integer (and also the fractional part) of the tunes. Remember that the betatron tune is the number of betatron oscillations of an off-axis particle around the ring circumference and therefore by extracting the betatron oscillation as previously explained one has just to count the number of full waves of the cosine like curve (eq. (2.2) or eq. (2.3)). In fact by doing that for the beam position envelope

resulting from all 96 BPMs of ELETTRA one should get an idea about the tune of the machine as one may easily verify from figure 3.1 (horizontal positions).

We have just seen how one may obtain the machine tunes by measuring beam position for 4 beam revolutions at a certain location. It is simply given by:

$$Q = \frac{1}{2\pi} \cos^{-1}\left\{\frac{1}{2}\,\frac{r_{n+1} - r_n + r_{n+3} - r_{n+2}}{r_{n+2} - r_{n+1}}\right\}$$

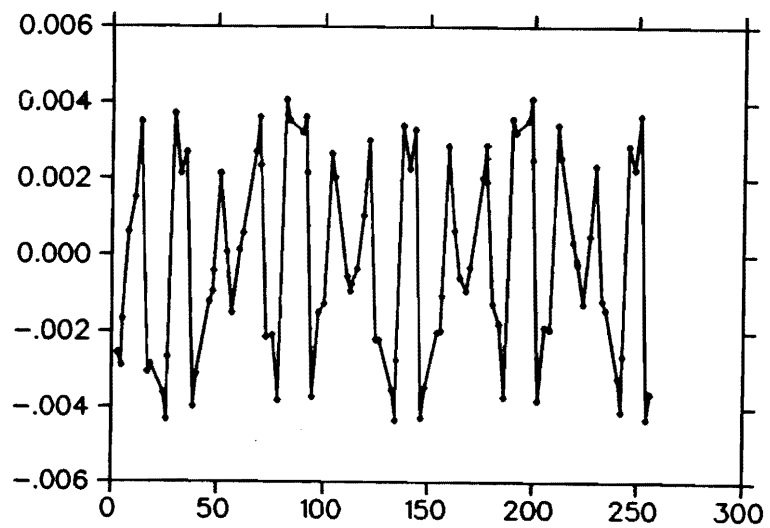


Figure 3.1

The above methods, although useful at the beginning, are rather inaccurate or not applicable for stored beam conditions with nominal functioning BPMs. Then a Fourier analysis of the closed orbit measurement data may be performed to find the harmonics of the orbit. This may be better appreciated if one expresses eq. (2.3) in the frequency domain:

$$y_{co}(s) = \sqrt{\beta_y(s)}\; Q_y^2 \sum_{k=-\infty}^{+\infty} \frac{f_k}{Q_y^2 - k^2}\, e^{i\,k\,\mu_y(s)/Q_y} \tag{3.1}$$

Eq. (3.1) shows that the optics acts like a very sharp filter resonating around the frequency Q. The Fourier coefficient f_k is given by:

$$f_k = \frac{1}{2\pi Q_y} \sum_{j=1}^{N} \sqrt{\beta_j}\; \theta_j\, e^{-i\,k\,\mu_j/Q_y} \tag{3.2}$$

By Fourier transforming and plotting the resulting amplitudes versus the harmonic numbers one will in general obtain a picture similar to figure 3.2. One may immediately see from that figure, that the integer part of the betatron tune is 15.

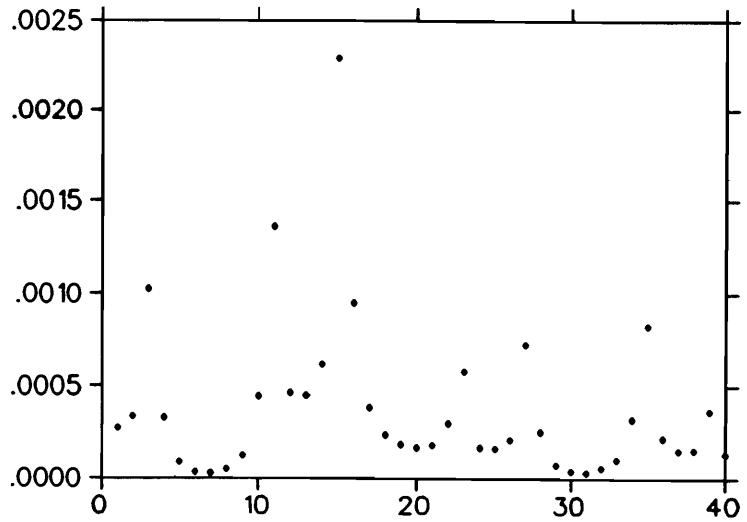


Figure 3.2

Applying power spectrum estimation techniques one may also obtain the full tune too. This is shown for the ELETTRA case in figure 3.3.

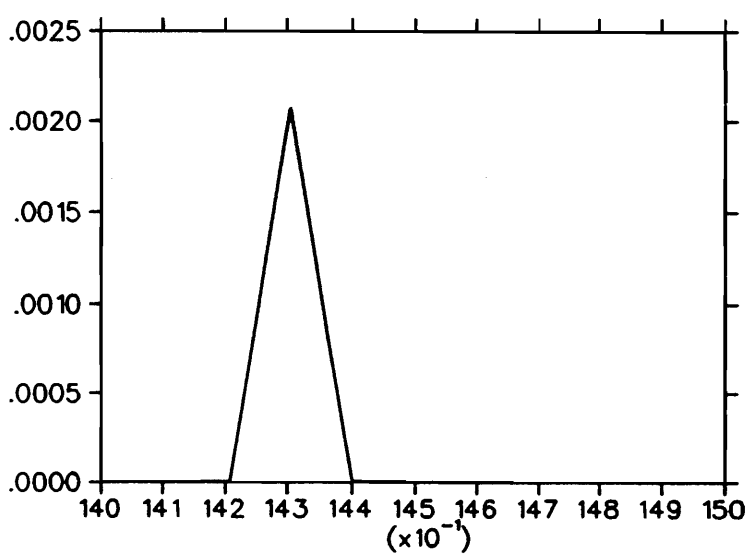


Figure 3.3

Since the kicks due to errors may not be strong enough for the tune measurement one usually excites the beam with an externally provided kick (e.g. use of the injection kicker or a stripline or a steerer). At the kick instant each particle starts a free betatron oscillation with the same initial phase but different frequency. However the frequency distribution will peak around the Q - frequency. This is the basic idea on which the tune measurement methods are based.

Since the tune should be measured precisely we intend to measure it using also the rf - excitation method (swept frequency method), rendering $\Delta Q/Q$ with an accuracy of 10^{-3} to 10^{-4}. A sinusoidal signal generator sweeping its frequency along the betatron frequencies will excite the beam via the stripline electrodes. Then a spectrum analyzer synchronized to the sweeping frequency and connected to a pair of pick-ups will analyze the beam oscillations providing the betatron frequency. In order to find the tune one then must simply divide the betatron frequency by the revolution frequency (according to the definition of the tunes).

It must be noted that strictly speaking what can be measured from one pick-up it is the fractional part of the betatron tune simply because observing oscillations at one pick-up one undersamples (i.e. samples the betatron frequency at the revolution frequency; to uniquely obtain the tune one should sample at a frequency at least double of the betatron frequency). The pick-up records the beam position at every passage and the signal is processed by fitting the position points, obtained after many revolutions, to a sinusoidal curve of frequency f_m. However such a frequency is not uniquely determined when undersampled but rather it is given by the fast (+) and slow (-) waves occurring at frequencies $f_m = (m \pm q) f_{rev}$ (for one bunch) where m is the frequency harmonic and q is the fractional part of the tune. For example for a vertical tune of 8.2 the lowest frequency of the vertical beam oscillation that can be observed is the fast wave $f_f = (0+0.2) f_{rev}$ or 230 kHz while the next frequency is the slow wave $f_s = (1-0.2) f_{rev}$ or 925 kHz etc.

Although this analysis may give very precise results, can determine neither m nor if q is above or below m however. To find the latter one must change the focusing properties of the machine and observe the direction in which f_m is shifted. In the following figure we show a typical picture of such an output.

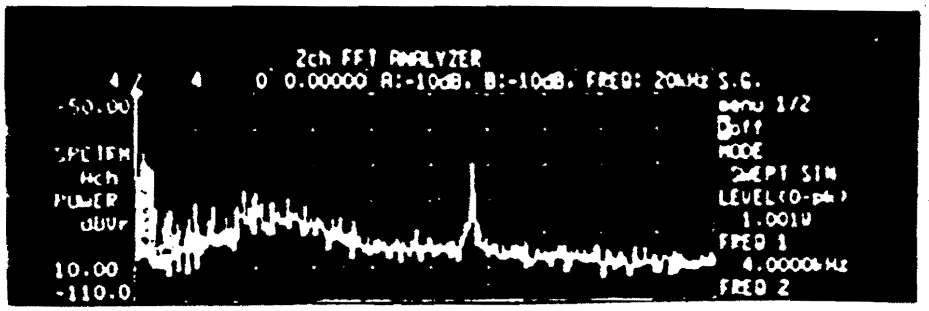


Figure 4.

The excitation strength must be high enough to bring the betatron sidebands above the noise threshold of the system. The shown peak indicates the betatron sideband where the resonance occurs and its distance in the horizontal axis (betatron frequency) from the beginning of the axis (left) is the Δf_β. If this picture corresponded to ELETTRA vertical tune measurement then Δf_β should be 231.32 kHz, since $q_y = 0.2$ and the revolution frequency is 1.1566 MHz.

One problem with spectrum analyzers is that the measurement is sometimes slow. The measurement time may be minimized by choosing a higher harmonic m. At low m however one has a better signal to noise ratio but this is more prone to signal deterioration from collective effects. For fast measurements at high resolution of may use the FFT (fast Fourier transform) signal analyzers. In this case one must choose to work at the low frequency harmonics.

Besides the limitations of the Fourier transforms, the spectral resolution of the system is determined by the duration of the transverse beam oscillations. For a damping time τ = 32 ms the full spectral width ΔQ of a damped beam oscillation is given by $\Delta Q = 2/\omega_{rev}\,\tau$ $(= 8.6\ 10^{-6})$.

The tune measurement system is necessary for chromaticity measurements and may also be used for beta function measurements and as a coupling diagnostic. The coupling may be observed if one introduces a horizontal deflection (e.g. using an horizontal steerer) and then measures the resulting orbit. In an ideal machine only the horizontal plane will be affected but in a real machine a small vertical orbit distortion is also observed. Maximum

5. Chromaticity Measurement

The chromaticity determines the change of the tune with the change of the momentum and is a very important optics parameter strongly influencing the beam stability. It is divided in horizontal and vertical chromaticity and defined as:

$$\xi = \frac{\Delta Q}{\Delta p/p} \tag{5.1}$$

For its measurement one employes the tune measurement system and the rf frequency. This is due to the fact that the rf frequency and the momentum are related and in the case of no field distortions (B constant) and very high γ like in ELETTRA, the relation is simply: $\Delta p/p = - a_p^{-1} \Delta f/f$ with a_p the momentum compaction factor.

Changing the rf frequency in the ELETTRA storage ring by 500 Hz one anticipates a horizontal tune change of $\Delta Q = 0.0263$. A $\Delta f = 500$ Hz at a frequency equal to 500 MHz will give a momentum shift $\Delta p/p = - 0.63\ 10^{-3}$ and putting all these into the chromaticity definition one obtains for the horizontal "natural" $\xi = - 41.8$ (Note that although the definition 5.1 is used at ELETTRA, sometimes in the literature or in other institutes the chromaticity definition may be also found as $\Delta Q/Q/\Delta p/p$). The "natural" chromaticity in modern storage rings is a negative number. Introduction of sextupoles at dispersive points allows one to control and therefore to vary the chromaticity towards positive values (see part II, head-tail instability).

In practice one plots a few points of tune versus rf-frequency and making a fit (tune is usually a non-linear function of frequency) one extracts the slope at the nominal operating rf-frequency.

6. Revolution Frequency, Central Orbit and Energy Measurement

It is desirable to know from measurements the length of the orbit or equivalently the central revolution frequency. To do this, one has to measure the betatron tunes as a function of the rf-frequency (see section 5). The procedure is repeated for different settings of the sextupoles i.e. for different chromaticities. In principle all these curves of the tune versus frequency graph should cross at a point which determines the central rf-frequency and due to the relation $2\pi R = h\,\beta\,c\,/\,f_{RF}$ one may obtain the length of the central orbit provided that β is known or else it may be deduced from the energy measurement.

The Energy could in principle be determined by measuring the speed of the electrons since this involves the path length (which we have already seen how one may measure) and the revolution period but in our case (electrons 1.5 GeV) the velocity is not a sensitive function of energy, being almost equal to c ($\beta = 0.999999942$).

A safer way to determine the beam energy of the ELETTRA storage ring would be by using the measured fields of the ELETTRA bending magnets since the total line integral corresponds to 2π radians of bend. Therefore the magnetic field measurements must be performed with high precision and detail. Using then the known formula $\gamma = E/E_0$ one may obtain the velocity via $\beta = (1 - \gamma^2)^{1/2}$ and hence as previously explained, the central orbit.

As an example let us assume that f_{RF} was measured to be 499654000 $\pm$ 200 Hz at the energy of 1.5 GeV. Then the central orbit will have a length C = 259.2000 $\pm$ 0.0001 m.

Absolute measurements of beam energy may be achieved using synchrotron radiation detectors. Higher accuracy may be obtained observing the Compton radiation scattered from a resonating cavity or a rf wiggler. This method can give $\Delta E/E$ to within 10^{-4} in about 10 seconds and for 1 mA intensity.

7. Dynamic Aperture Measurement

To ensure that the motion will remain bounded for long periods of time, the betatron amplitudes $A_{\beta\ x,y}$ (t) must be at any time less than a finite boundary A. The maximum of the $A_{\beta\ x,y}$ (t) amplitudes, for which the motion is bounded defines the dynamic aperture. The transverse dimensions of the vacuum chamber define the physical aperture and obviously the optimum case is when the dynamic ≥ the physical aperture.

Measuring the aperture is important since it gives useful information about peculiarities in the beam motion (e.g. non - linearities) especially when many insertion devices are used. Direct measurements are needed to check the validity of the tracking studies and to further understand the machine behaviour. It is also one of the main factors controlling the beam intensity and consequently the beam lifetime.

One can measure the dynamic aperture by exciting the stored beam with a kicker to a short lifetime and then measuring it as a function of the position of the scrapers. These devices are destructive for the beam and one may introduce them transversely at will (2 + 1 vertical and 1 horizontal are foreseen for the ELETTRA ring) into the vacuum chamber thus restricting the physical aperture. As long as this aperture limitation lies outside the stable region of motion the lifetime should be constant, whereas when it starts restricting the motion a clear reduction of the lifetime should be observed; the distance of the scrapers at that instant corresponding to the (x or y) dynamic aperture of the ring.The output for such a measurement called also "scraper-lifetime measurement" might look like as follows:

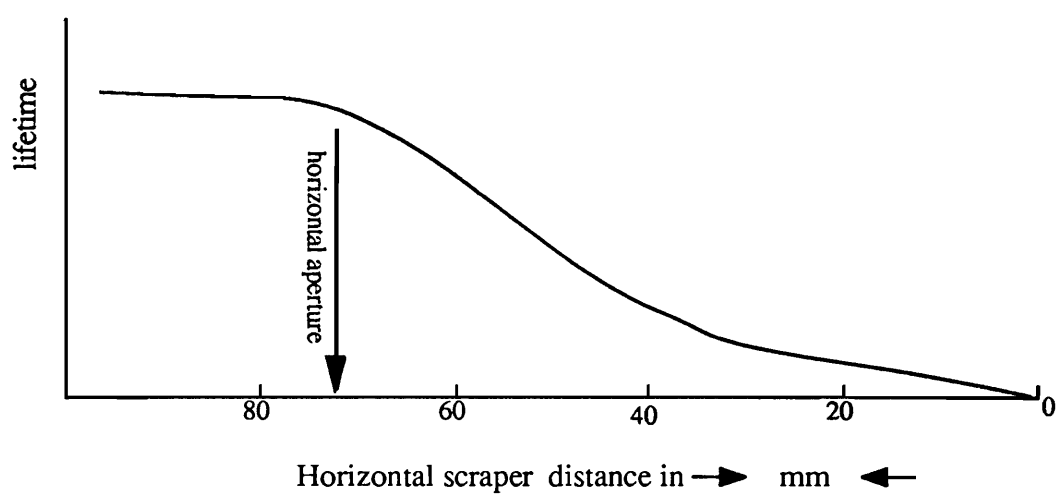


Figure 5.

From the figure 5 it is immediately evident that the horizontal dynamic aperture is ~ 75 mm. The same method may be also used to determine the dynamic aperture as a function of tune so that one may compare it with tracking studies and device improvements. Because the beam is usually off-axis care must be taken in determining the beam-scraper relationship.

One may also perform the measurement without using scrapers, by exciting a betatron oscillation and increasing its amplitude until beam losses occur. The losses will show up as a reduction of lifetime. For exciting betatron oscillations the kickers and/or steerers can be used.

Sextupoles reduce the dynamic aperture. Measurements of the dynamic aperture after the installation of the insertion device(s) must be also performed.

8. Momentum (Energy) Acceptance Measurement

The momentum acceptance is the analog of the dynamic aperture for the longitudinal space. It defines the maximum momentum deviation that a bunch may have so that the motion of the particles remains bounded in the longitudinal space. The bucket acceptance defines the maximum momentum spread a bunch may have if it is placed in the "energy" center of the bucket while coupling and non-linearities are ignored.

To measure the momentum acceptance one is using the relation $\Delta p/p = - a_p^{-1} \Delta f/f$, (for B constant) a_p being the momentum compaction factor, and measures for different settings of f_{RF} the lifetime. For a certain $\pm\Delta f$ the lifetime is constant whereas for values outside $\pm\Delta f$ a certain reduction of lifetime is observed. Such a measurement therefore will show a plateau as indicated in figure 6:

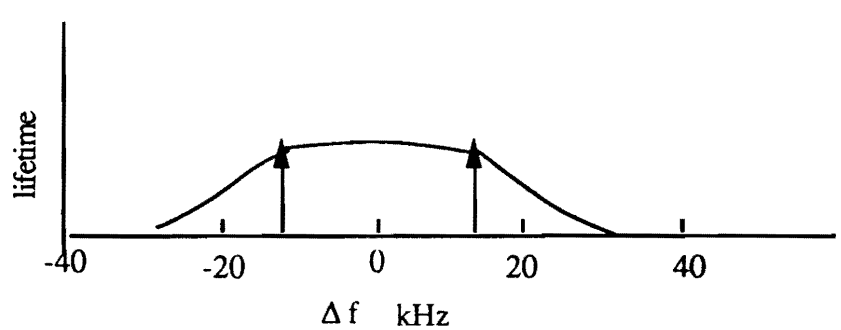


Figure 6.

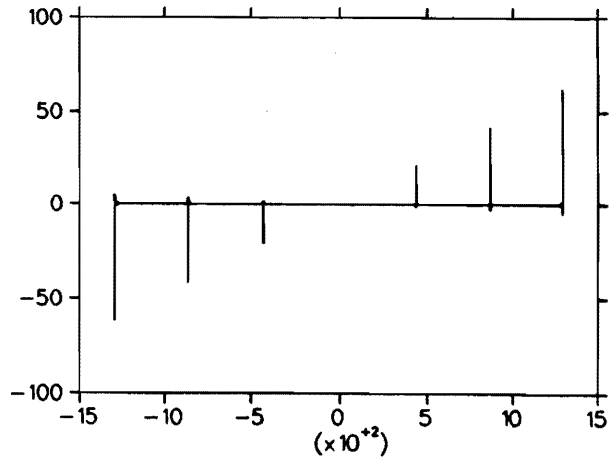


Figure 9.

In reality the above lines will be folded onto the positive x-axis and will have a finite width representing the frequency spread between the particles of the bunch as it was previously explained; by measuring that spread, the natural $\Delta p/p$ may be found. It is worth noting that the area of each band is a measure of beam intensity and for the same band area the pickier the curve is, the "cooler" are the bunches.

As an example, from the ELETTRA data we have that the natural $\Delta p/p = \pm 6\ 10^{-4}$ which corresponds to a frequency spread $\Delta f/f \sim \pm 10^{-6}$ or $\Delta f \sim \pm 500$ Hz on the fundamental. Therefore by measuring with a spectrum analyzer a bandwidth of about 1 kHz we shall know that the momentum spread is as designed.

A tune spread provides one of the two important mechanisms for fighting "naturally" instabilities. The transverse needed betatron tune spread is given approximately by the formula:

$$\Delta Q \geq 1 / (\pi f_0 \tau_T) \tag{9.1}$$

Inserting the ELETTRA numbers and assuming $\tau_T \sim 1$ ms one obtains a $\Delta Q = 2\ 10^{-4}$ Transverse instabilities (having a growth time greater than 1 ms, ignoring radiation damping) will be damped if the tune spread is greater or equal with the above quoted value.

A position sensitive pick-up will deliver Schottky signals from the betatron oscillations. If the beam is well centered the spectrum will consist of lines at $f_m = (m \pm Q)\, f_{rev}$ (for one bunch) and therefore the fractional part part of the tune may be extracted by a simple inspection whereas no excitation of the beam is needed (compare with section 3). However like in the longitudinal case the lines will have a frequency width Δf_β which may be used to determine the natural ΔQ using the relation $\Delta Q = ((m-Q)(\Delta f_{long}) - \Delta f_\beta)/f_{rev}$. One may notice that this measurement is independent of the momentum compaction factor.

Finally another way to measure the energy spread is by utilizing the dispersion (see section 14).

10. Intensity Measurements

The beam intensity will be measured by a DCCT current transformer. These instruments use the magnetic field induced by the beam to evaluate the DC average beam current I_b from which it is possible to deduce the charge Q and the number N of particles in the beam:

$$Q \equiv N\, e = I_b\, T_0 \tag{10.1}$$

where $T_0 = 2\,\pi\, R\,/\,\beta c$ is the beam revolution time and N is the number of electrons. The DCCT's are very sensitive and can measure intensities as small as 5 μA over a dynamic range of several hundred mA.

The time structure of the bunch may then be found, if it is taken to be Gaussian (which is usually true for electrons at 1.5 GeV), from:

$$I(t) = I_b \frac{\sqrt{2\pi}\, R}{k_b\, \sigma} e^{-\frac{1}{2}\frac{(c\,t)^2}{\sigma^2}} \tag{10.2}$$

where k_b is the number of bunches, σ the rms bunch length and R the mean ring radius. The bunch spectrum may be easily seen in the frequency space i.e. the Fourier transform of (10.2) using a pick-up and an oscilloscope preferably triggered by the ring clock thus obtaining also the beam fill.

The signal from the DCCT monitor after being processed may be displayed on a screen as intensity against time:

Touschek lifetime measurements may be performed by varying the rf voltage. The phenomenon is due to single large-angle Coulomb scattering within one bunch. Due to this scattering a particle may obtain a relative $\Delta p/p$ that exceeds the longitudinal or transverse acceptance and therefore will be lost. The Touschek lifetime is proportional to the rf voltage.

Since the beam chamber vacuum can not be perfect (e.g. outgassing due to synchrotron radiation) the particles of the beam will scatter off the residual gas molecules in two ways: a) elastic b) Bremsstrahlung. The gas scattering lifetime is inversely proportional to the vacuum pressure and at low energies the elastic scattering is dominant while at higher energies the Bremsstrahlung is dominant. The effects of the macroparticles (dirt) can be also investigated. Their effects may be identified from abrupt glitches in the intensity and lifetime graphs.

Lifetime experiments should be also performed in order to study the effects of the ions and ion trapping in the beam. The ions are created from the beam-residual gas collisions and are focused when an electron bunch is passing, executing transverse motion in the potential well of the bunch, while after the bunch passage they simply drift. The trapped ions accumulate until their space charge forces become strong enough to produce a defocusing kick to the bunch. This effect is one of the primary beam current limiting factors in electron synchrotrons. Direct observation of the effect may be achieved by using a Bremsstrahlung detector and different beam fillings. The observed Bremsstrahlung counts the number of the residual gas atoms and trapped ions. However the trapped ions Bremsstrahlung yield is proportional to the beam filling while the residual gas Bremsstrahlung does not depend upon the way one fills the ring. One may also try to blow up the beam (e.g. using the Q - measuring system) as a further check since the trapped ion bremsstrahlung yield is inversely proportional to the transverse beam dimensions. A long gap without electrons (asymmetric ring filling) and/or the use of special clearing electrodes may help. The effect disappears if one uses a positron instead of an electron beam. Comparing lifetimes for electrons and positrons is another way to examine effect of the ions in the ring.

12. Beam Profile Measurements

The size of a bunch in the ELETTRA storage ring resembles that of a short hair. With dimensions (1 σ) of about 5 - 15 mm in length and of about 0.1 mm in width, it is not an easy thing to measure. However the beam dimensions is one of the basic parameters of the machine and should be carefully measured whereas due to the required smallness of dimensions very good resolution is required.

For the transverse beam size and somewhat after the initial stage of commissioning we intend to use the synchrotron light coming out of a bending magnet. The light after being processed will be focused on a charged coupled device (CCD, 576 by 550 cells). The image on CCD will be the transverse beam profile and may be directly measured. A typical picture of a possible electronically processed output is shown in figure 12. Assuming 0.1 mm/div the upper part could be the vertical whereas the lower part the horizontal beam profile in the storage ring. Profiles may be also obtained by using hard X-rays detectors.

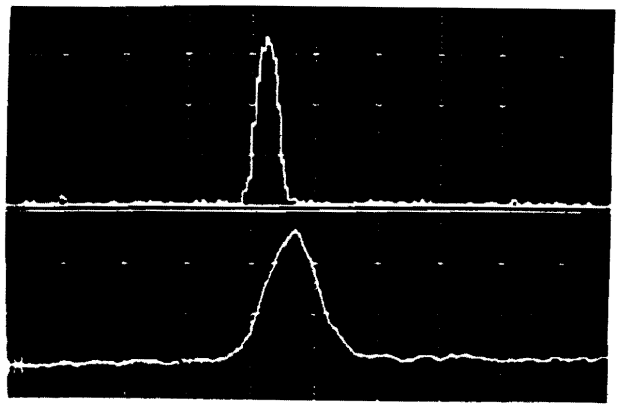


Figure 12.

At the initial stage of commissioning i.e. injected beam, we intend to measure the profiles using fluorescent screens (FS, destructive monitors). These are simple scintillator screens that one may drive into the beam path at will and at an inclination of 45°. The screen is illuminated through a small window whereas through another window at 90° to beam direction, a TV camera will obtain the 2-dimensional image of the beam. These instruments are also useful in showing the position of the orbit. Figure 13 shows how such a picture might look:

Figure 13.

In that case the scale was 1:1 and the very thin screen was placed just after the injection septum so that one could see the injected as well as the circulating beam (before its attenuation). Note that not all screens allow the particles to go through. The ELETTRA screens are 6 mm thick. Such a screen is very useful for injection optimization too.

To measure the bunch length one may again use the synchrotron radiation visible light. This is due to the fact that the light pulse emitted by a bunch has in most practical cases the same time structure as the bunch itself. What one then does is to observe the extracted from the bending magnet light, with streak cameras (resolution 2 ps) or fast photodiodes (resolution 30 ps). Since the shortest bunch length in our case is about 3.5 mm (1σ) the photodiode resolution is at the limit whereas for the single bunch mode (14.6 mm 1σ) the resolution is sufficient. Alternatively one may use a small well-matched electrode and feed the signal into a very fast sampling (~ 20 ps) oscilloscope.

The pictures one obtains from such measurements, are similar to those shown in figure 12. There also exist other methods for profile measurements except utilizing the synchrotron light, to be discussed later.

13. Emittance Measurements

The Emittance is a very important (basic) parameter, comprises in one number the dimension and angular (or energy) divergence of the beam and depends from the optic. Although its basic mathematical definition is straightforward, confusion and ambiguities exist when considering the following questions:

a) with or without π ;
b) normalized or unormalized and
c) the % of beam included.

For latter use we present a short introduction into the matter in order to clarify the subject and introduce a common language.

Any pair of conjugate variables (q,p) in a conservative system define a constant "area" due to Liouville's theorem. Mathematically one writes: $A = \int p\, dq = \text{constant} = m_0 c \beta\gamma \int q'\, dq$ where $q' = dq/ds$. For fixed energy we see that the integral $\int q'dq$ = constant. Observing the trace of the circulating particles against a screen one may see that those are confined inside a closed curve, usually an ellipse and then the integral $\int q'dq = \varepsilon\, \pi$ = Emittance. Since the area of an ellipse is π a b with a,b the ellipse semi-axis we see that ε = a b. In the transverse space a is the relative transverse dimension and b is the divergence, whereas in the longitudinal space a is bunch length in phase and b is the momentum deviation.

As we have seen one may take as the transverse emittance ε = a b or equally π a b. We will use the first form: ε = a b, the reason being that the value without π can be directly connected to the beam size. Sometimes in the literature and/or in other laboratories the π is also quoted as a reminder that we refer to an ellipse (e.g 5 π mm rad, where ab = 5 mm rad) but it is never taken into account in calculations.

In a conservative system the above quoted emittance is not a constant during an energy change (e.g. during acceleration it will shrink). Therefore it is convenient to define the normalized or invariant emittance as $\varepsilon^* = \beta\gamma\, \varepsilon$. The invariant emittance is usually quoted in linacs, transfer lines and hadron rings. If the system is lossy e.g. an electron synchrotron, Liouville's theorem does not apply therefore no invariant area can be defined and thus the notion of invariant emittance is meaningless. What is then quoted is simply the emittance ε = ab which is also called the natural or equilibrium emittance (since it is determined from the balancing between the radiation and the quantum excitations).

ELETTRA storage ring the dispersion is zero in the straight sections where the insertion devices will be positioned; however in the bends and in other places there is dispersion reaching a maximum of 0.4 m.

Dispersion measurements are needed in order to make sure that really no dispersion exists where it should not exist. Such measurements may be performed by using the position pick-ups and the relation $\Delta p/p = -a_p^{-1}\, \Delta f/f$. The ELETTRA BPMs measure the perfect closed orbit i.e. the terms inside the square brackets in eq. (2.1) (if the BPMs were measuring each turn an averaging over many turns would provide the perfect closed orbit). Symmetrically changing the rf frequency above and bellow the nominal value one has $r_1 = X - D(s)\, a_p^{-1}\, \Delta f/f$ and $r_2 = X + D(s)\, a_p^{-1}\, \Delta f/f$ and therefore $D(s) = (r_2 - r_1)\, a_p\, f / 2\, \Delta f$. To have r in the range of mm (for X=0) one needs momentum deviations of at least 0.25 % corresponding to a rf frequency change of the order of 2 kHz.

Non zero dispersion in the rf cavities may lead to synchro-betatron coupling, which is usually an undesirable effect. The dispersion in the insertion device regions should also be zero, otherwise an unwanted (from the users point of view) increase of emittance occurs due to quantum excitations. The dispersion may be corrected by using the steerers.

The formula $x_{\delta i} = D_{xi}\, (\Delta p/p)_i$ may be also used to determine the momentum (energy) spread, provided that the dispersion is well known. To measure the beam profile one may use the methods described in section 12.

15. Injection

The injection of the beam into the ELETTRA storage ring will be performed from the inside of the storage ring on the horizontal plane. A straight section is dedicated to this operation which will be accomplished by 4 kicker magnets symmetrically placed around the mid point of the straight section and a radially adjustable septum. The ring can not be filled with one linac fill therefore multiturn injection is necessary. This complicates matters since the kickers are not fast (4 μs pulse) compared with the beam revolution time (865 ns).

15.1 On-Axis Injection

On axis injection is useful because one avoids the induced coherent betatron oscillations and therefore the study of orbit distortions due to misalignments and field errors may be easier studied. For on axis injection a DC bump may be used to move the closed orbit towards the septum. The septum and the first kicker bend the injected beam to the design trajectory so that the beam crosses it exactly at the second kicker. This kicker bends then the injected beam onto the closed orbit. It is obvious that due to the kicker speed we can not accumulate the injected beam.

15.2 Off-Axis Injection

The injected beam enters the storage ring chamber parallel to the design orbit therefore the two kickers after the septum downstream will be used to bring the beam towards the design trajectory while the 4 kickers will collaborate to produce a local bump for the stored beam. A DC bump may be also used to bring the closed orbit near the septum, however this bump should be kept small not to disturb the acceptance. In this operating mode one can accumulate the stored beam.

15.3 Injection Efficiency

Under this name we mean all the necessary action needed to (completely) match the beam coming into the ring, with the ring parameters (100 % efficiency).

Critical buttons for this operation are: transfer line optic, the linac to ring timing, the kicker pulse (duration and voltage) and the septum voltage (as fine tuning). What one tries to achieve is to inject in the middle of the bucket (linac, timing-kicker pulse, rf-phase), to occupy all the needed buckets (timing), to inject in the middle of the dynamic aperture (septum -kicker) and to match the dynamic aperture with the injected beam emittance (linac and transfer line optic).

The efficiency is always given as the ratio of the delivered intensity over the given intensity so that $E\% = 100 * Q_{FINAL} / Q_{INIT}$. If the intensity measuring pick-up inside the ring displays the circulating current then (only for the ring) $Q = I_0 T_0$. If for example a linac works at 10% efficiency it means that the intensity delivered is only 10% of its

intensity capability. Ring injection efficiency of 90% means that 10% of the injected electrons are lost.

Before increasing the injection efficiency, the acceptance of the storage ring should be improved. For this purpose a stored beam is required. One then should turn off the DC bump (if used in the injection) before the orbit correction programs are applied. While improving the acceptance the tune must be monitored.

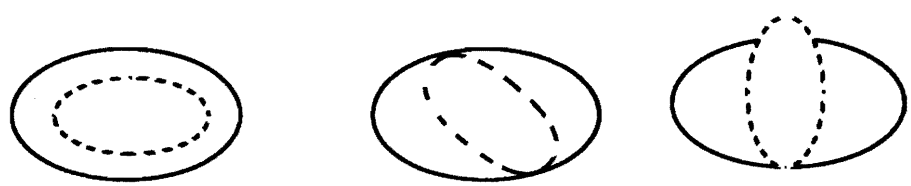
Another important aspect for good injection efficiency is the timing in multibunch as well as in the single bunch mode. In the multibunch mode the ring must be filled by some 2.16 10^{12} electrons divided amongst many buckets ($\leq$ 432) of 2 ns length each. The delivered linac pulse can be up to 150 ns long containing 1.9 10^{10} electrons with a repetition rate of 10 Hz. Therefore every linac pulse will occupy up to 75 adjacent ring buckets while 115 linac pulses are needed to bring into the ring the wanted intensity and the minimum time (highest injection speed) needed for the operation will be 12 s at 100% efficiency. The maximum injection speed will be therefore 121 A/h.

Due to ion trapping problems it may be advisable to fill less than 432 buckets i.e. letting some buckets unoccupied. If this is indeed the case then the simplest way would have been to fill all the 432 buckets with the nominal intensity per bunch and then kick out of the machine the wished number of bunches. However this simple scheme can not be realized due to rather long kicker pulse (4 μs). Then the other solution is to fill the wanted buckets specifically. One observes that the closest multiple of 75 to 400 is 5 therefore 375 adjacent buckets may be filled letting 57 empty buckets at the end. In the first five pulses the first 75 buckets will be totally filled and so on. Since the linac repetition rate is 10 Hz one must wait an integer number of revolutions to inject again in the same bucket for the 5 shots. In 0.1 s (10 Hz) the bucket has made 115660.67 revolutions and it will appear again in the same place at the 115661th revolution which corresponds to a time t = 0.1 s + 0.284 μs. Obviously any integer number of revolutions will do, if one wishes a larger time on the μs part. If for example one waits for 120 10^3 revolutions the second shot should occur at a time t = 0.1 s + 3.752 ms, keeping this timing for the 5 first shots. However the 6th shot will differ again in time since now we want to fill the 76th up to 150th bunch. Then the time shall be as the previous one but shifted by $t_s = - T_0 / 75$ or 0.0115 μs. However here we can not delay a multiple of t_s because 432 / 75 is not an integer. If instead of a 150 ns pulse there would be a 144 ns then 72 buckets would be filled in every shot and because 432 / 72 = 6 we would be more flexible in time shifting. The pulse duration may be controlled at ELETTRA.

In the single bunch mode we want to fill one bucket of the ring with 4.6 10^{10} electrons from linac pulses of 1 ns long, 10 Hz repetition rate containing 10^9 electrons. The pulse fits well into one bucket (2 ns) whilst 46 pulses are needed therefore the minimum filling time will be 4.6 s and the maximum injection speed will be 6.6 A/h. Here any bucket will do and if the timing is locked onto any pilot bucket , some bucket will be consistently filled provided that the timing does not err in more than 0.5 ns. The single bunch mode may be also used for filling the ring with more than one bunch but at a much lower speed than in the multibunch mode.

The ELETTRA control system can pre-programme up to 100 different pulse timings so that specifically filling the bunches is not a problem.

Another important issue influencing the injection efficiency is the emittance matching. It might well be that the injected emittance occupies a smaller area than the dynamic aperture but one axis of the emittance ellipse is greater than that of the corresponding aperture. In this case it might occur that the emittance projection is placed in such a way into the aperture that some parts of it remain out, resulting to partial beam loss and therefore decreasing the efficiency. In the following figure 14 we illustrate 3 cases of matching:



perfect matching acceptable matching unmatched

Figure 14.

To correct a badly matched beam one should modify the transfer line optic by operating on some quadrupoles as well as the kicker - septum parameters in case of large beam displacements.

To <u>optimize the injection</u> one should keep in mind the following recommendations:

High acceptance (good orbit correction procedures), tunes not near resonances, stable injection timing operation, adjust phase between rf and injection, beam energies between transfer line and storage ring adjusted, injected beam in the middle of the septum, injected beam in the horizontal plane of the closed orbit, strong kicker bump. If DC bumps are also used must be well optimized.

16. Synchrotron Tune Measurements

As we have already seen (section 2) the synchrotron tune is the analog of betatron tunes in the longitudinal space. Knowing the synchrotron tune is very useful for calibrating the rf parameters and for machine studies since many collective effects are influenced and/or influencing it. Finally synchrotron tune is useful since it sets the time scale, for the time classification of the collective effects and of the adiabaticity. The "natural" synchrotron tune is given by the formula:

$$Q_s^2 = \frac{a_p\, h\, eV_{RF} \cos \varphi_s}{2\pi \beta^2 E} \tag{16.1}$$

and as we see, it is independent of the amplitude (therefore only linear motion is considered i.e. natural). In general the tune is amplitude (bunch length) dependent due to non linearities of the potential; it is a known fact that in full buckets at the edge of the bunch the synchrotron tune is zero. In practical cases for long bunches this difference from the "natural" frequency could be an order of magnitude. However for the ELETTRA ring such a large spread is not expected, because of the very short bunch in a very long bucket (20 mm and 600 mm respectively) and the "natural" tune is practically the same for every particle in the bunch. The ELETTRA ring tune is (at 1.5 GeV) 0.011 and accordingly the "natural" synchrotron frequency is $f_s = Q_s\, f_0 = 12.896$ kHz i.e. a particle will execute a full synchrotron period in 77.54 μs or in 90 revolutions.

The adiabaticity time is usually 2-3 synchrotron periods and therefore changes in the rf voltage or magnetic fields should rise from initial to final value in at least 200 μs. Faster changes may result in filamentations and fast beam losses even though electrons are "naturally" damped since the radiation damping time is an order of magnitude higher.

From the synchrotron tune one may also find the synchrotron frequency spread that provides one of the two important mechanisms for fighting "naturally" instabilities. The longitudinal Landau damping time is given approximately by the formula:

$$\frac{1}{\tau_L} = \frac{2\pi f_s}{16}\left(\frac{h}{R}\sigma_l\right)^2 \tag{16.2}$$

and inserting the ELETTRA numbers one finds approximately $\tau_L = 146$ ms, meaning that instabilities having a growth time larger than that (in the absence of radiation damping), will be damped. The longitudinal instabilities of ELETTRA however have growth times

of the order of 16 μs and therefore this mechanism could help only if τ_L was of the same order or equivalently if the synchrotron frequency spread is of the order of 62.5 kHz. This could be achieved for example if the harmonic number h becomes 38 times bigger (19 GHz cavity e.g. Landau cavity) or the bunch longer or a combination of those two, the dependence scales as $\sim h^2\sqrt{h}\,\sigma_l^2 / R^3$.

From the above discussion it is clear that at some stage of the commissioning, the synchrotron frequency and spread should be measured. As we have said and shown in section 9, the spectral lines from a longitudinal pick-up after a FFT is performed, will appear at multiples of the revolution frequency. When the synchrotron motion is taken into account these lines are shifted to the frequencies $f^+ = h\,f_0 + f_s$ and $f^- = h\,f_0 - f_s$ (fast and slow wave sidebands, the picture is identical to that in figure 8 but horizontally shifted by 0.01 - ELETTRA ring value - left and right of the $h\,f_0$ line) which may be directly observed on a spectrum analyzer. This is so because in an electron storage ring there is enough noise to sufficiently excite coherent synchrotron oscillations of observable amplitude. One can check that the spike observed is really f_s by changing the rf voltage as it may be readily seen from eq. (16.1). However one may not be able to distinguish the feeble synchrotron sidebands amongst the huge revolution harmonics and therefore a narrow band filter is required. If the noise level is less than -60 dB then such oscillation must be driven. This can be achieved by phase modulating the rf voltage or by driving a pair of stripline kickers at the synchrotron frequency. Finally as far as the spread is concerned remember that the sidebands are having a measurable width readily observable as described in section 9.

17. Epilog

This report is written to help the non experts to get familiar with the various measurements during the first stages of machine commissioning. To this extend in section 1 a standard commissioning strategy was briefly mentioned, in order to provide a logical measurement framework.

During the measurement presentation it was unavoidable referring also to the theoretical background on which the particular measurement is based as well as briefly introducing the needed instrumentation.

However in order to perform the described measurements one must get some beam inside the ring. Here are some tips for a successful start:

- Try to know well the parameters of the machine before starting the commissioning.
- Start from the beginning after a shutdown.
- Always cycle the magnets before/after switching them off/on.
- Always check for ripples in the various power supplies.
- Before injecting check for any left inside scrapers and/or vacuum interlocks.
- For each new action activate again the orbit correction programs.
- In vacuum conditioning, do not forget that vacuum improves with time, so be patient.
- Always check the reproducibility of the machine.
- With rf off the beam will survive only for a maximum of 80 revolutions in ELETTRA.
- 1 mm error in ELETTRA ring circumference corresponds to 2 kHz rf-frequency shift.
- If nothing works DON'T PANIC.

A second part dealing with measurements related to intensity dependent (e.g. collective) effects and machine impedance will shortly follow.

APPENDIX

Table 1.

MEASUREMENT	INSTRUMENTATION
First turn steering - orbit check	FS / BPM
Betatron Tunes	BPM & SE
Phase advance and Beta function	BPM / SE
Chromaticity	SE & RF
Central rev. frequency, orbit / Energy *	SE & RF
Momentum acceptance and spread	DCCT / SE & RF
Dispersion	BPM & DCCT / SE & RF
Dynamic aperture	SE & Scraper
Beam profiles	FS / SLM
Emittance *	Scrapers / SLM
Intensity *	DCCT
Lifetime *	DCCT / SE
Injection efficiency	DCCT / BPM / FS
Impedance and intensity dependent effects	DCCT / SLM / SE

(*) The most important parameters.

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