# OPERATIONAL EXPERIENCE WITH ELETTRA

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## ABSTRACT

ELETTRA early in its commissioning phase exceeded its design goals to provide the community with one of the world's brightest sources of VUV and soft X-ray radiation. The facility is now in its second year of routine operation. The source brilliance and lifetime are the figures of merit for a high output of successful user experiments. A description of the activities pursued at the facility to guarantee the quality of the light and reliability of the source along with an account of the experience gained in operating the facility is given. A summary of future upgrades to further enhance the brilliance is described. Finally a status of the machine performance will be presented.


## 1 SCHEDULE

The Italian third generation radiation source ELETTRA came into operation in October 1993. During the commissioning year 1994 the amount of beam time dedicated to User experiments was increased from 25% to 75%. Since the start of 1995 the facility has routinely provided synchrotron radiation for experiments. During that year the number of hours for which the storage ring was run was 5024 hours of which 3784 were dedicated to Users. During 1995 the amount of time allocated to machine optimisation studies was decreased from an initial 25% to 20% at the end of the year. The present year has seen this further reduced to 17% (excluding start-up) which is thought to be the minimum without compromising operational efficiency. The total running time for 1996 is 6096 hours of which 4968 will be for Users. The number of hours foreseen for 1997 will be the same. The facility is run on a three or four week basis followed respectively by one or two week shutdowns.

## 2 DESCRIPTION OF THE FACILITY

ELETTRA is a 1.5 to 2.0 GeV electron storage ring. The facility can provide photons for experimental stations with a brilliance of $10^{19}$ photons/(s $mm^2$ $mrad^2$ 0.1%bw). As its injector it uses a linac that provides electrons at an injection energy of 1.0 GeV. The final energy is then achieved after ramping the beam in the storage ring. The ring has an expanded Chasman-Green structure with a periodicity of twelve. The main machine and operating parameters are given in table 1. Of the twelve straight sections, eleven are used for insertion devices. The insertion devices are 1.5m long and three of them can be used per section. About the straight sections, triplets are positioned which can be used for optics compensation of the insertion devices. The injection elements, four fast kicker magnets and the septa, occupy the twelfth straight section. The ring is supplied with four single cell radio-frequency cavities placed in the dispersion sections.

| | |
|---|---|
| Optimised Energy | 1.5 - 2.0 GeV |
| Circumference | 259.2 m |
| Emittance (2.0 GeV) | 7.0 nm-rad |
| Natural Energy Spread | $7.9 \times 10^{-4}$ |
| Tunes | 14.3 (h), 8.2 (v) |
| Spurious Coupling | ~1% |
| Beam Size at ID | 238 (h), 14(v) μm |
| Beam Divergence at ID | 30 (h), 5.5(v) μrad |
| Orbit correction | 0.2 mm (rms global)<br>0.002 mm (local) |

Table 1: Machine parameters

At present the facility has 45% of the available straight sections with fully operational insertion devices (see table 2). An EEC funded joint project between ELETTRA, BESSY and MAX-Lab will produce an electro-magnetic elliptical wiggler. The installation date for the device is August 1997. Five beamlines are operational and another four will be by the end of September this year. One of which is the first bending magnet beamline. The beamlines provide photons in the range 20 to 35000 eV.

(a)

| Beamline | ID(cm) | N | Gap [mm] | Bo[T] | K |
|---|---|---|---|---|---|
| ID2 | U5.6 | 81 | 27 | 0.444 | 2.34 |
| ID3 | U12.5 | 36 | 28 | 0.506 | 5.91 |
| ID5 | W14.0 | 30 | 22 (20) | 1.5 (1.6) | 19.6 |
| ID6 | U12.5 | 36 | 28 | 0.506 | 5.91 |
| ID7 | U8.0 | 19 | 26 | 0.709 | 5.30 |

(b)

| | | | | | |
|---|---|---|---|---|---|
| ID4 | EEW<br>20.0 | 15 | 25 (v)<br>50 (h) | 0.50<br>0.08 | 9.0<br>1.5 |

Table 2: (a) Installed ELETTRA insertion devices (b) Electromagnetic Elliptical Wiggler

## 3 OPERATIONAL EXPERIENCE

The principle characteristic of all third generation light sources is the output of highly brilliant light. An extremely desirable user condition is also the requirement of a long lifetime. Particular emphasis has therefore been put on the control of the orbit and multibunch instabilities which is reflected in the manner in which the facility is operated. Furthermore the possibility of extending the brilliance has been pursued.

### *3.1 Operation*

At present the storage ring is provided with 1.0 GeV electrons which are then ramped to the final energy of 2.0 GeV. The ring is operated in multi-bunch mode with 80% filling to eliminate ion-trapping. No request to operate in single bunch mode has been voiced so far. The current is limited to 250 mA (see below). The filling procedure is made semi-automatic via a high-level software package which performs the basic operation of cycling, loading, variation and control of rf parameters, insertion devices, front-ends and filling pattern. The speed of all power supply variations has been increased to reduce unavailable beam time. Prior to June 1995 ramping was performed by a linear variation of parameters with a tune feedback system active. This procedure has been improved and modified to perform a multi-file ramp utilising a non-linear current variation which makes the tune feedback redundant. Ramping from 1.0 to 2.0 GeV can be performed in 100 seconds, and in routine operation 300. The linac provides typically 2-3 mA/s and the storage ring has a capture efficiency >90%. The overall time from beam dump to delivering light to experiments has been reduced to 22 min, however, in practice this approaches 30-40 min. The orbit is routinely corrected to 150-250 microns which is sufficient to guarantee a high quality beam. Furthermore angle and position at the source point in the insertion devices is corrected to zero position and slope and maintained there by a high level slow feedback program (see below). The ramping constraint on a refill increases the importance of long beam lifetime and greater component reliability. An increase in lifetime is made at the expense of small bunch dimensions and controlled use is made of coupled bunch instabilities which lengthen the bunch[6]. In conjunction to detailed monitoring of the modes using a spectrum analyser and post-processing programs, regular use is made of active beamlines to examine the effects of the modes on the quality of the light. An increase in electron beam energy spread slightly broadens the line-shapes and reduces the flux of ID spectra, this is however, compensated by an increase in lifetime. Lifetime for Users in the “relaxed” machine condition is 18 hours at 250 mA whilst for an “optimised” machine it is 9 hours at the present total rf gap voltage of 2.5 MV.

### *3.2 Stability*

Beam stability can be categorised in long, medium and short term disturbances. Long term effects seen over a period of a year are related to ground settling. Measurements of main magnet positions were performed twice a year after the start-up of the facility (1993) and are now performed on yearly basis (1995). The results show a marked reduction in settlement as time progresses. A reduction of 0.5 mm rms is found. Associated with seasonal changes and ground expansion is an increase in the ring circumference of 0.2 mm. This is compensated by shifting the radio frequency. The changes in storage ring radio frequency also requires a fine re-adjustment of the cavity temperatures for stable operation.

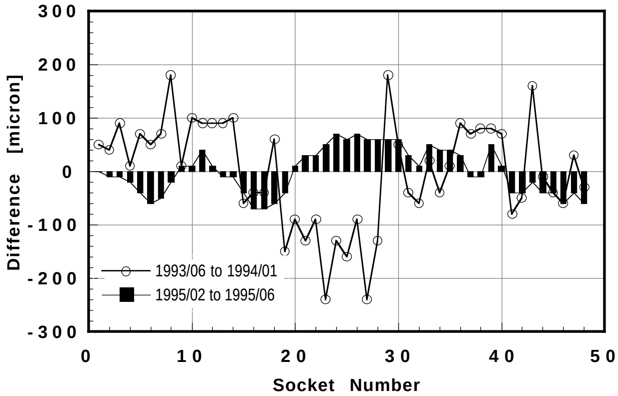


Figure 1: Settling at the facility has lessened during the second year.

In general the stability of the facility is excellent. The main cause for transverse beam motion is a slow drift due to thermal effects after a new filling is performed. A correlation can be made between an orbit drift over one hour in the horizontal plane of ~0.06 mm and the stabilisation time of about one hour of the main magnet cooling circuit after a ramp is performed. The temperature variation of the water corresponds to about 1°C over this period of time. Figure 2 shows an occasional daily variation of the horizontal orbit over a 24 hour period with a peak to peak variation of 0.03 mm, probably due to ambient temperature variations. Over short time scales the orbit is generally quite stable, especially in the vertical plane. Figure 3 shows the variation of position and slope at the source point of the VUV beamline. The motion in the horizontal plane is more noticeable with variations of tens of microns.

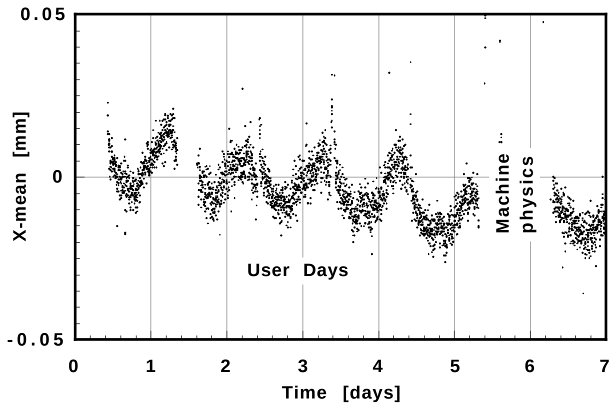


Figure 2: Twenty-four hour variation in the horizontal plane of the closed orbit mean. The drift over the week corresponds to 0.01 mm.

These slow motions are corrected by a slow local feedback system operating at a high level [1]. The system controls and if necessary corrects the orbit at the centre of the insertion device straight sections every few minutes. The method utilises an empirical calibration to minimise the leakage of the closed orbit bumps. In the horizontal plane five correctors are used to maintain a constant path length.

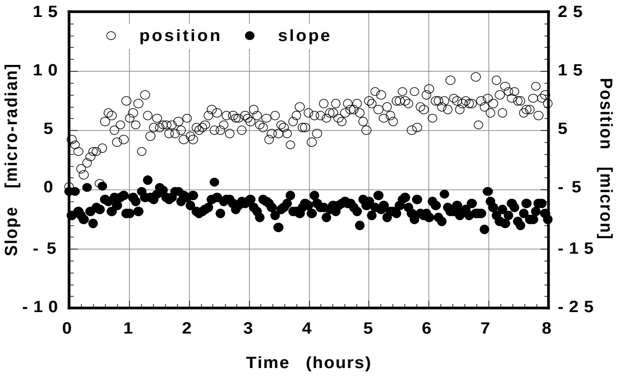


Figure 3: Eight hour variation of the vertical source point in an insertion device. No corrections or gap variations were performed during this period. Current decay: 200 to 160 mA at 2.0 GeV.

### 3.3 Lifetime

Vacuum in the ring is good with better than 0.07 nTorr static pressure and a peak value of 1.5 nTorr at the light ports with 250 mA and 2.0 GeV (elsewhere 0.15 to 0.6 nTorr). These values have remained practically constant during the past year of operation. Gas scattering effects are observed at vertical apertures of ±5 mm. The smallest internal aperture in the ring is at present 15 mm leaving room for improvement in insertion device performance.

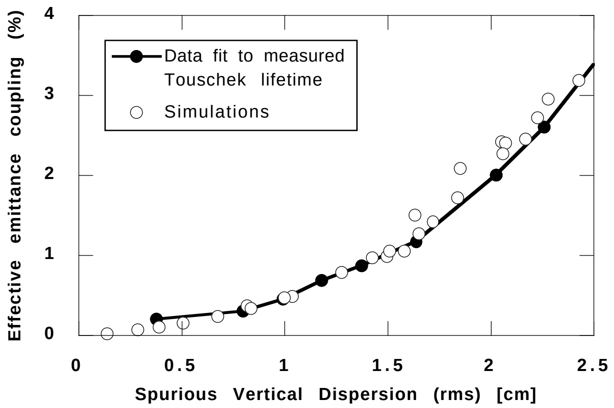


Figure 4: Simulations of the effective emittance coupling generated by statistically distributed closed orbit distortions compared to data extracted from fitting Touschek lifetime measurements (2.0 GeV).

The lifetime[2] at ELETTRA is dominated by the Touschek effect. Therefore control of the vertical dispersion has a strong influence on the lifetime. The vertical closed orbit is typically corrected to 0.2 mm rms and the dispersion to 3 mm rms (see below). Measurements of the lifetime in single bunch mode for various residual dispersions nicely confirm simulations, see figure 4.

### 3.4 Insertion Devices

Operation with insertion devices results in tune shifts, closed orbit distortions and a reduction in dynamic aperture[3]. The effects are inversely proportional to the square of the beam energy. At 2.0 GeV a tune shift of 0.03 is observed with all devices at their minimum gap which is compensated by optics adjustment. The dynamic aperture reduction of 1 mm seen at the injection energy is absent at 2.0 GeV. Beam motion associated with gap changes of the insertion devices is compensated by correction coils mounted on the undulators. The coils can compensate large changes of undulator gaps such that at another beamline the intensity variation of the third harmonic is below $10^{-2}$. For small gap changes the variation is below $10^{-3}$. The wiggler utilises rotating blocks for the compensation. A local feedback system using photon BPM’s has been developed and undergoing final tests. The system will be used to allow individual beamlines limited control of insertion device gaps. With the future use of bending magnet beamlines particular attention is being paid to orbit reproducibility at the bending magnet source points. A global orbit feedback system interleaved with local feedback's for the control of orbit stability is foreseen.

## 4 DEVELOPMENTS

### 4.1 Lower emittance

Studies have been initiated towards the implementation of a lower emittance optics[4]. The optics adopted releases the constraint of zero horizontal dispersion in the insertion device straight sections. The optics, with sextupole distribution optimised, reduces the emittance by approximately a factor of two, from 7 to 3.7 nm-rad. The sextupoles were re-optimised for the compensation of the chromaticity and an optimisation of the geometric aberration. Simulations show that the resulting dynamic aperture, however, is 50% lower than with the normal optics. Further understanding of the new optics is required. The finite horizontal dispersion in the straight sections necessitates tight control of longitudinal multi-bunch instabilities, since the resulting dispersion will increase the overall beam dimensions in the presence of energy spread. Examination of the effective emittance at the source points show, however, that one still obtains a smaller beam size even with twice the natural energy spread. In the bending magnets the effective emittance of the new optics as a function of rms energy spread is clearly more favourable than the nominal optics, see figure 5.

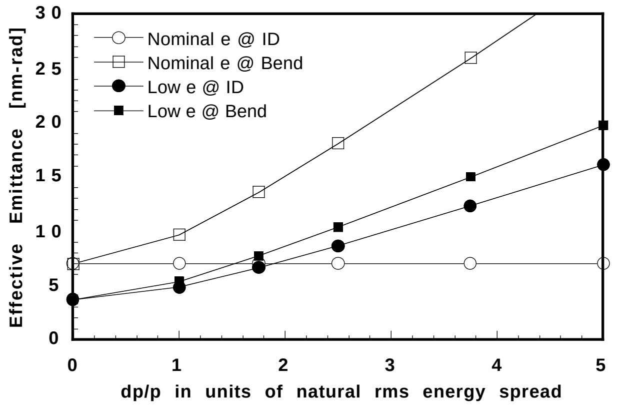


Figure 5: Effective emittance in the presence of energy spread. Comparison of low emittance and nominal optics.

## *4.2 Orbit control*

Third generation light sources with their strong focusing greatly amplify magnet misalignments. The tight tolerances on the alignment has resulted in low geometric coupling of the natural emittance. Consequently the spurious vertical dispersion is the main source of effective emittance coupling. Simulations confirmed by experimental observation show that the expanded Chasman-Green lattice with a gradient in the bending magnet is particularly sensitive to the generation of spurious vertical dispersion due to closed orbit errors.

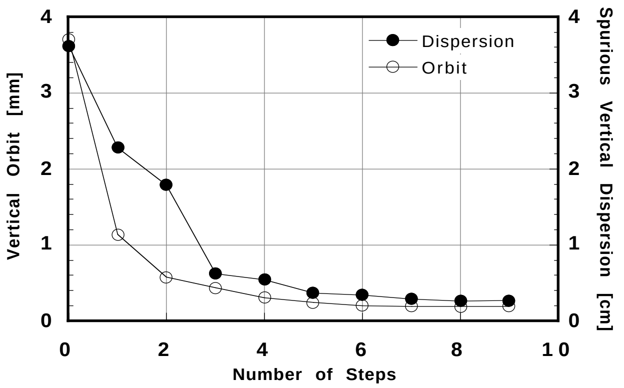


Figure 6: Simultaneous correction of spurious vertical dispersion and orbit as a function of number of corrections. Final values of 2.2 and 0.19 mm respectively.

Closed orbit rms's as little as 0.2 mm can still lead to an rms dispersion of 2 cm. Quadrupoles and sextupoles both contribute strongly to the dispersion, however, they fortunately tend to cancel each other. The contribution from steerer magnets is negligible. The correction of the vertical dispersion has been actively followed up[5]. This is now achieved in combination with global orbit correction, see figure 6. The algorithm adopted is Singular Value Decomposition applied to the sensitivity matrices of dispersion and orbit as a function of steerer kicks. The method is particularly attractive in that the constraint for constant path length can be implemented as an extra row in the matrix equations. The technique results in small correction values per steerer magnet and shows rapid convergence compared to single correction of either dispersion or orbit, which was found tedious to perform since correction of one quantity tended to spoil the other.

## *4.3 Multi-bunch Instabilities*

Another important aspect of operation is the control of multi-bunch instabilities[6,7]. The instabilities manifest themselves as a broadening and reduction of the undulator line-shapes associated with increased beam energy spread. They also affect the lifetime. The longitudinal modes are corrected by temperature tuning of the cavities. The single cell cavities are mechanically compressed to tune the fundamental accelerating mode during the temperature changes. The longitudinal instabilities are generally not current limiting, whereas the transverse multi-bunch instabilities result in partial or total beam loss. It is observed that transverse instabilities become apparent when the longitudinal modes are suppressed.

The success of the tuning depends on the distribution of modes and their growth rates as a function of cavity temperature. With the present configuration longitudinal modes are controlled. Transverse modes also require tune and chromaticity adjustment because of an unfavourable distribution of these modes in some cavities. The distribution can be greatly modified by acting on a cavity with a small plunger (Higher Order Mode Frequency Shifter HOMFS). This works in shifting the fundamental which is mechanically corrected to the desired value. The higher order modes, however, are redistributed in the process and this permits further temperature optimisation. The most damaging modes are the longitudinal L3 and transverse T3[7], these modes tend to cover a large temperature range. A fixed HOMFS was used to shift the L3 mode on one cavity with success. In the latter half of this year an adjustable HOMFS, currently undergoing characterisation, will be installed on a storage ring cavity. Within a year all ELETTRA cavities will be provided with adjustable HOMFS's allowing a more complete control of the transverse modes.

A long standing problem of occasional low frequency beam oscillations (up to 100Hz) was resolved to be due to particular coupled bunch excitations that generate coherent longitudinal oscillations with subsequent de-coherence via Landau damping followed by radiation damping[8]. The oscillations are eliminated by a judicious choice of cavity temperatures.

## *4.4 Controls*

The integrated brilliance of the facility can be compromised if reliability of systems is too low or the amount of non-useful time (i.e., injection, ramping, etc.) is too long. The latter is optimised by a high level process manager, the One Button Machine, "1bm" which automates repetitive tasks. The program is a task spawner that executes different tasks concurrently following a predefined logic flow. It allows easy operator intervention during its execution with error recovery and step-by-step on-line help. To enhance fault recovery a new alarm server has been implemented[9]. It permits analysis and logging of failures and assists in preventative maintenance of components.

Support programs for beam and machine component control form an essential part of the arsenal used to guarantee high quality output of light. To free more time for useful machine studies the amount of time spent in routine characterisation of machine parameters has to be minimised. Towards this goal, in addition to the standard software described elsewhere, a program which performs automatic orbit correction, dispersion correction, tune and chromaticity adjustment is being commissioned. The program is useful for the generation of intermediate files for energy ramping. Another program “trouble”[10] which assists the operator to trouble-shoot is based on the history of all experience in trouble-shooting and fault recovery. The program guides the operator with a series of questions, the answers of which permit the choice of subsequent questions or measurements to be performed until a conclusion is drawn.

## 5 SYSTEMS PERFORMANCE

User downtime to systems failure has systematically decreased over the last two years yielding an overall uptime of 91%. During the last twelve months this has been 93%. This was mainly due to improvements to linac operation, power supplies and the understanding of cavity interlocks (HOM driven). A major source of downtime is electrical disturbances from thunderstorms. This can account for up 50% of summer interruptions and overall 20% of annual downtime. The uptime in the absence of storms exceeds 95%. The rf system has proven to be flexible and allows operation of the machine even with a reduced number of rf plants.

## 6 FUTURE UPGRADES

New vacuum chambers for insertion devices will be constructed having internal apertures of 15mm and externally 17mm. The chamber has an elliptical cross-section with no pumping along its length.

At present the maximum beam current (250 mA) exceeds the original design value of 200 mA at 2.0 GeV. To further increase the brilliance and flexibility of the facility the current will be increased to a maximum of 400 mA at 2.0 GeV or the energy increased to 2.4 GeV with 200 mA. As reported in a previous article[11] the cooling of the vacuum chamber was enhanced to be able to increase the current. This resulted in a substantial reduction in the outgassing and chamber movement, however, at currents exceeding 250 mA heat load problems still exist. This issue is being actively pursued.

With the present current at 2.0 GeV and with the constraint to ramp the storage ring the temperature tuning of the cavities is sufficient for the control of both longitudinal and transverse multibunch instabilities to satisfactory levels. It is, however, expected that higher currents, i.e., 400 mA, may render the mechanism more laborious for routine operation. For this reason a transverse feedback system will be developed. The foreseen system will selectively damp dangerous transverse modes, while the longitudinal modes will be controlled with temperature tuning.

The linac is actively involved in up-grading many of its systems[12-14]. These include timing, diagnostics, vacuum monitoring and most importantly the entire control system. The original system has been a major source of system failure. The up-grade will increase reliability and allow full integration to the storage ring system. A longer term development is the installation of extra accelerating sections which will permit the existing sections to be studied and improved. The additional sections will also provide full-energy injection for new storage ring operating modes, for example the use of mini-undulators.

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