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OPTICAL CAVITY ALIGNMENT AND MIRROR DAMAGE IN THE LELA FEL EXPERIMENT

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The alignment of the LELA optical cavity, 17.5 m long, is described. The procedure to attain a close alignment of the undulator radiation axis and the cavity axis using an external laser is reported. Measurements of Q from stored light spectra are presented. Mirror degradation at increasing integrated electron currents is considered.

1. Introduction

In the period between September 1985 and March 1986 relevant progress of the LELA experiment has been obtained, both in cavity alignment and mirror reflectivity protection.

The main characteristics of the experiment and the work performed in the former stages have been extensively reported [1].

Since March 1986 experimental activity has been interrupted for a storage ring shutdown. At start-up in autumn 1986 the LELA experiment should benefit from some machine improvements: a new vacuum pipe, replacing the 20 year old one, should contribute to reduce beam instabilities. An improved beam position monitor and orbit correction system will assure a better beam handling capability. It will be useful when a new lattice, designed to increase the LELA optical amplification by a factor ≈ 3, will be set up. This new lattice has a dispersion-free section at the undulator location to minimize the bunch horizontal spread. It has already been tested, but it was impossible to use it currently due to too large closed orbit errors.

Before the last shifts at the beginning of 1986 few changes have been made to the cavity. The vacuum pipe from both mirror vessels to the pumping points has been enlarged to reduce the impedance and lower the static pressure near the mirrors. The pumping power near the downstream mirror has been doubled and a partial pressure gas analyser has been fitted there to monitor periodically the carbon partial pressure near the mirror. Minor work has been done to speed up mirror substitution to reduce vacuum contamination during these operations. A vacuum quality improvement of an order of magnitude has been obtained.

2. Transverse alignment

The goal of this alignment is to overlap the electron beam profile and the fundamental cavity mode in the undulator to maximize the stimulated emission by the trapped radiation. The unusual features of our cavity, whose design was extensively described in ref. [2], entail a few complications in its operation. The cavity is 17.5 m long and its mode waist is asymmetrically placed with respect to the end mirrors. The tolerable range of error for angular and transverse displacement between optical axis and electron beam trajectory is 15 μrad and 0.2 mm at the center of the undulator. Such severe requirements can be accomplished by actuating mirror movements with piezoelectric translators (called PZT in the following). The PZT pusher system, used for final adjustment of the cavity, has been designed to operate under computer control. Mirror movements can be easily combined in such a way to provide a parallel displacement or tilt of the cavity axis. The control program also takes into account nonlinearity and hysteresis cycles of PZTs. The cavity axis can move in the range $\approx \pm 4$ mm and $\approx \pm 8$ mrad, although this range is reduced if combined motion has to be done.

The alignment of the cavity is accomplished in three steps. First the axis of spontaneous radiation is tracked as carefully as possible with an argon laser beam, then the cavity heads are set to get a few laser reflections between mirrors. Finally, when the cavity axis joins the

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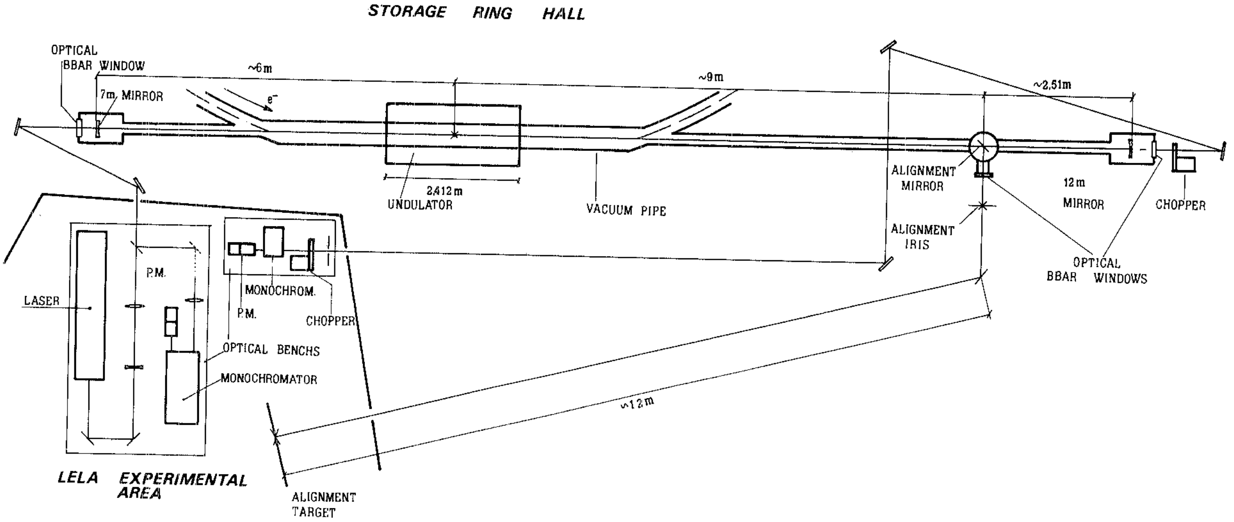

Fig. 1. Layout of the LELA experimental area.

radiation axis within the PZT range, further adjustment is done by means of PZT pushers maximizing the stored light intensity.

In fig. 1 a layout of the experimental area around the cavity is shown. When the storage ring is operating nobody is allowed to stay near the machine outside the experimental area bunker; the first two steps of the above-described procedure have been planned taking into account health physics requirements.

The first step is the most cumbersome and difficult. The radiation light cone, originating in the undulator, is extracted from the cavity by the alignment mirror (see fig. 1); two points are taken along its path, at alignment target and iris, as apart as possible in order to minimize error amplification when tracking back the cone axis with the laser beam. In spite of all care, due to the badly defined contour of both beams, a few millimeter error cannot be avoided between the laser and the radiation axis at the undulator position; this error becomes even larger when the radiation axis is extrapolated backward to the upstream mirror. Most of our troubles come from such a large error, leading to a marginal overlap of the cavity axis to the upstream mirror. Furthermore, a boring snag has to be overcome in these operations. A lateral displacement of the alignment laser beam introduces an unwanted angular deflection when passing off center through the upstream mirror; it acts indeed as a thin prism, whose opening angle depends on the radial distance, yielding a deflecting power of ≈ 40 μrad/mm. So an iterative procedure has to be applied to have the laser beam passing through the reference points and the upstream mirror center; thereafter transverse displacements of this mirror are no longer allowed, otherwise the reference line would be lost.

The second step is to align the mirrors in such a way that a few round trips of the laser beam are obtained. Usually optical cavities can be carefully aligned on an optical bench with an external laser mode matched to the fundamental cavity mode. In our case such a careful alignment would not be sufficient, because of the above-mentioned error between laser and undulator radiation axes; mode matching itself turns out to be very hard to realize due to both the long distance between laser and cavity, and the cavity length; furthermore, the upstream mirror affects the input beam as a defocusing lens and a reliable waist measurement is obtained only after a lengthy beam profile scanning. An identical cavity was built in air to study the problem; a folded optical path allowed mirrors to be put aside for easier control. Observation of spot sizes by varying the beam waist showed a critical dependence on this parameter. We realized that a simpler matching would work effectively for our purpose. The laser beam was enlarged to get a nearly constant profile in the first cavity pass; in this way we were able to see enough reflections to align the cavity before the laser beam diverged. At this stage the cavity optical axis, defined by the line through the mirror centers of curvature, intercepts both mirrors and independent mirror movement is no longer required.

Up to now only mechanical movements have been done; often these operations required a coordinated action at two points ≈ 18 m apart. There has been no mirror exposure to undulator radiation. From now on only fast operations should be performed with low stored current to avoid mirror degradation until a complete alignment is achieved.

The LELA operation usually requires three equally spaced bunches circulating in the storage ring; then, since the cavity length is half of the bunch spacing, the light emitted by the electrons passing through the undulator overlaps the light pulses in the cavity. However, the correction of the misalignment between the cavity and radiation axis is performed with only one bunch in the storage ring. In this way a 350 ns time interval lasts between light emissions inside the cavity and the evolution of the light pulse can be observed during the following two round trips.

The light emerging from both cavity mirrors is brought to the LELA experimental area, where work is safely permitted even with the storage ring filled. A double setup, composed of a monochromator and a photomultiplier, allows independent measurement of the light pulses from both cavity ends. Due to the low mirror transmittivity a weak signal comes from the cavity axis, while stronger diffused light rays can pass through the mirror holder openings. To take care of these spurious rays some irises have been used to collimate the radiation along the undulator axis. An effective rejection of stray light is obtained and the S/N ratio is improved. The monochromators are set for ≈ 20 Å bandpass centered around 6300 Å; this wavelength selection strongly contributes to discriminate against unwanted signals. The photomultipliers are C31034 type and equipped with a special GaAs photocathode to ensure a good sensitivity to red light. The PM signal can be seen on a scope and further elaborated to obtain information about cavity tuning. The reference timing with respect to the circulating bunches is given by an external clock locked on the rf frequency.

Scanning of the cavity axis position is then carried out by means of the PZT pushers. When the cavity axis moves towards the radiation axis, light begins to be reflected between mirrors and pulses are detected by the photomultipliers. The system is very effective in bringing the first reflections into the mirrors. A clear signal can then be seen on the scope in the form of a train of pulses delayed from each other by the cavity round-trip time. The pulse height equality ensures that the reflected beam is completely contained within the mirror surfaces during the first two round trips. The pulse height increases when more reflections are brought towards the mirror centers. Unfortunately the photomultiplier pulse height is a very noisy signal. Further optimization, when only a small contribution from higher order reflections adds to the signal, requires a more sophisticated pulse height analysis. A synchronous demodulation system is used. It is the same, with minor changes, used in amplification measurements [3]. The light beam is chopped at ≈ 1 kHz to create sidebands around the 8.56 MHz fundamental harmonic in the frequency spectrum. By mixing the PM output signal with a 8.56 MHz local oscillator the low frequency modulated signal is extracted and its amplitude measured by a lock-in amplifier. It must be emphasized that reliable operation of such a system requires a stable carrier spectrum; on the contrary in the single bunch operation mode, as previously described, the fundamental harmonic moves from 2.85 MHz, when the cavity is misaligned, to 8.56 MHz, when the cavity is perfectly aligned with radiation.

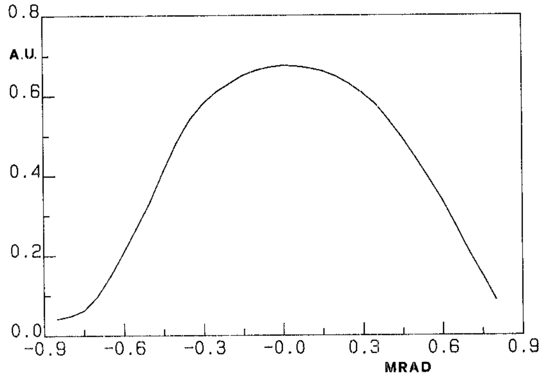

Fig. 2. Intensity of the stored light vs transverse cavity axis tilt.

The next operation is to fill the storage ring in the three bunch mode, taking care of storing the same current per bunch. It is remarkable that both cavity and accelerator stability are sufficient to keep a good alignment for a long time, and a comparable alignment condition is usually found after each new injection.

The cavity axis is then sequentially displaced and tilted, both radially and vertically, to optimize the output signal from the demodulation system. When the light stored in the cavity reaches a high level, a red spot becomes evident within the mirror shadow from the upstream head; a visual check of the relative position of cavity axis and mirror center is then possible. If this red spot is not well centered, a lower light level than usual results. Sometimes our optimization efforts to raise its value were unsuccessful, showing that the cavity alignment was still diffraction limited when the limits of the

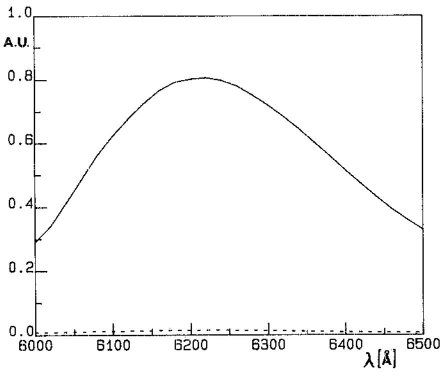

Fig. 3. On-axis spectrum of light coming out through the downstream mirror under two conditions: cavity tuned (continuous line), cavity detuned (broken line).

PZT range have been attained. A typical detuning curve, where light intensity from an end mirror is plotted vs cavity axis tilt, is shown in fig. 2.

After a satisfactory alignment has been achieved, a precise Q measurement is performed. We define Q as the ratio between the light intensity stored in the cavity and the light emitted by the electrons in the undulator at each turn. As the mirror reflectivity band is larger than the undulator peak, wavelength scanning is carried out to get the maximum of the transmitted radiation spectrum. The same procedure is then performed, after mirrors have been tilted to detune the cavity, to measure the light intensity directly coming from the electron bunch. A background contribution is given by the synchrotron radiation coming from the bending magnet and is measured by switching off the undulator. Its intensity turns out to be of the same order of magnitude as the direct radiation and has to be subtracted to get the correct ratio. A sample of these curves is shown in fig. 3; normalization to the same electron current has been applied; monochromator and PM spectral response have not been taken into account. Q measurements will be considered more extensively when dealing with mirror damage.

3. Longitudinal tuning

When the transverse alignment procedure was well established, and confidence about Q measurement reliability was obtained, a preliminary longitudinal tuning (i.e. a cavity length measurement) has been attempted by optical means. Before this the distance between the cavity mirrors could be known only from mechanical measurements performed outside the vacuum vessel; a concrete shielding wall is between the cavity heads and prevents a direct measurement of the mirror spacing. We estimate that this measurement implies an error not less than a few centimeters; however, the distance between the mirrors can be adjusted by more than this uncertainty by means of bellows inserted along the vacuum pipe. A rough spacing of 17.50 m had been set between the mirrors during assembly of the cavity and mirror vessels. Operations for fine transverse alignment do not affect the distance between the mirror centers. A tuning range of ± 1.0 cm, with a mean step of 1.25 μm, is allowed by a micrometric screw, pushing the mirror holder along a jump-free rail. The final adjustment for optimal tuning has to be done within 7 μm, which could hardly be handled by the micrometric screw. A PZT pusher has been fitted in series with the screw to allow a finer control of the mirror spacing; in this way an overall resolution better than 0.1 μm over 17.5 m can be obtained for longitudinal tuning.

A mirror displacement ΔL causes the light pulses coming from the light stored in the cavity to lead or lag with respect to the light pulses coming directly from the electron bunch, according to shortening or lengthening of the cavity with respect to the optimum mirror distance. The cavity losses determine the pulse height decrease in the following round trips, so that the envelope of the light pulses from the cavity exhibits an exponential tail on one side; the slope is given by $\alpha = c/(2Q\Delta L)$, where c is the speed of light. In a real measurement a few shortcomings of this simple scheme must be taken into account. The light pulse natural width is ≈ 1 ns long, which is much longer than the pulse spacing at reasonable ΔL, and its intensity is too low to be detected by a fast photodiode; so a direct measurement of the pulse spacing and an independent Q measurement from pulse height decrease rate is impossible.

Nevertheless the light pulse shape can be detected by a fast photomultiplier, and intensity fluctuations can be smeared off by averaging over many pulses. The major drawback of using a photomultiplier is the distortion of the pulse shape on the long trailing edge due to small impedance mismatching.

Two pulse shape measurements have been accomplished by moving the downstream mirror at two different positions 1.5 cm apart. A deconvolution has been applied to the measured pulses, assuming a proper value of risetime to take into account contributions from PM bias, cable and sampling head capacitance. Two values of ΔL were obtained; their difference was consistent with the applied mirror displacement, so we relied upon them as absolute cavity length measurements. The mirror spacing appeared to be 1 cm shorter than required even at the maximum distance attainable with screw operation; so the cavity has to be stretched by ≈ 2 cm to put the screw range centered about the optimum length.

Such a length error, and the UV damage already affecting the mirrors, prevented any observation of spontaneous radiation amplification.

4. Mirror damage

Our cavity has been designed to have diffraction losses $< 10^{-5}$ to best exploit the low gain available. Limits to its Q are set by mirror losses, which cannot be lower than a few 10^{-4}. Furthermore mirror reflectivity is strongly affected by UV flux in the higher harmonics of undulator radiation. Our aim in this stage was to measure the mirror degradation rate and to study the correlation between mirror losses and damaging agents.

Previous experiments [4] found a cooperative action of UV radiation and carbon contamination, leading to an irreversible chemical alteration of SiO_2 into SiC in the first mirror layers. A different source of reflectivity loss is due to the hard UV component, producing absorbing F-centers along the thickness of the multilayer mirror. Such damages can be recovered by a prolonged heating.

In the first stage of cavity operation we used commercial laser grade mirrors, whose initial reflectivity was 99.8%. Damages due to both causes were observed and have already been reported [5]. Since then the cavity vacuum system has been largely improved, as has been described in the introduction, and a more accurate analysis of these effects became possible. Electron current and exposure time were carefully monitored during undulator operation to have an estimate of UV flux impinging on the downstream mirror surface. A periodic analysis of residual gas composition in the cavity head was performed to monitor the carbon content.

The mirrors used in the last shifts had an initial reflectivity in excess of 99.97%. We have carried out only preliminary measurements of residual reflectivity; the spectrophotometer we used to measure it has a sensitivity not larger than 1%. In spite of this limitation an insight of the damaging mechanism can be obtained by analyzing the reflectivity band deformation. Three mirrors have been used in the last shifts. Two of them were put in the downstream cavity head; they were exposed to integrated electron currents of respectively 600 mAh (sample 1) and 1700 mAh (sample 2). The third mirror, inserted in the upstream head, was never substituted until shutdown. None of them shows delamination or a dark band due to carbon incorporation. After heating their reflectivity has recovered to more than 99%. The mirrors in the heads of our cavity are affected in a different way. The upstream mirror is hit only by radiation reflected by the other mirror, so that superficial UV damage should not be relevant. In spite of this, the samples previously used showed a dramatic reduction of reflectivity down to ≈ 70%, but it was largely recovered after 28 h of heating at 220 °C. We guessed that this was caused by the intense hard radiation in this area during injection in the storage ring. A lead shield was interposed between the cavity head and the injection area; its thickness was enough to stop scattered electrons at injection energy. After this operation the upstream mirror remained in the cavity for three months of continuous machine operation and no reflectivity loss was measurable within the spectrophotometer sensitivity. Both samples of downstream mirrors showed a reflectivity decrease down to ≈ 97% (sample 1) and ≈ 95% (sample 2); in both cases the reflectivity recovered after heating. The reflectivity curves for sample 2, before and after heating, are shown in fig. 4. When the difference between the reflectivity curves before and after heating is made a broad absorption peak appears in the red band of the spectrum. This indicates that mirror reflectivity is affected by F-center absorption created by UV or soft X-ray flux.

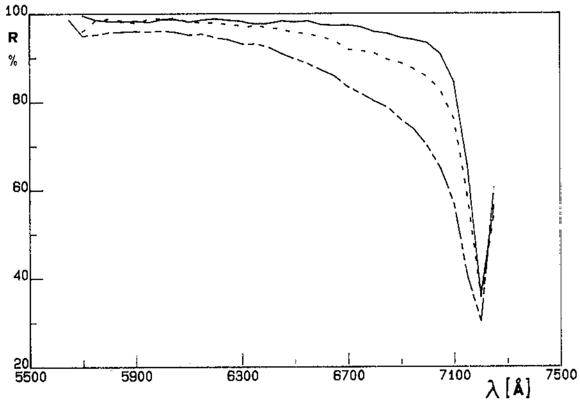

Fig. 4. Reflectivity curves of the downstream mirror exposed to 1700 mAh integrated current (continuous line); the broken lines are the reflectivity curves measured during and after 220 °C heating.

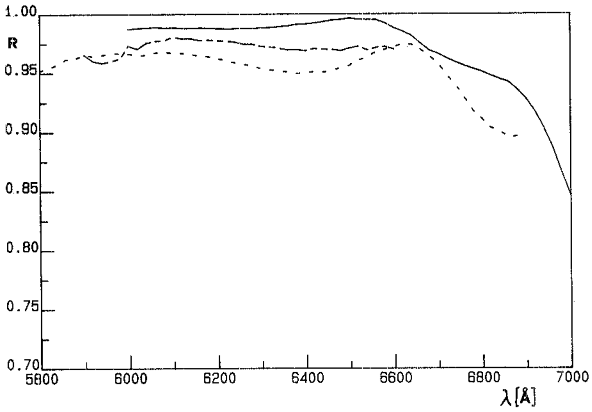

Fig. 5. Reflectivity curves calculated from light spectra as in fig. 3. The curves correspond to reflectivity after exposure to 770 mAh (continuous line), 1100 mAh (mixed line) and 1700 mAh (broken line).

In such a situation the reflectivity loss rate when new mirrors are inserted in the cavity is the most relevant feature to take into account to successfully operate an FEL. We assume at least some Q measurements were not affected by diffraction losses. Then the cavity Q depends only on mirror losses. The spectrum of the stored radiation at a given Q contains information about mirror degradation inside the cavity. The reflectivity curve for three different integrated electron currents, as obtained by stored radiation spectra and taking into account the spontaneous radiation spectrum and the measured Q's is shown in fig. 5. In spite of the small number of data a reflectivity decrease rate of $\approx 3 \times 10^{-5}$ mA^{-1} h^{-1} can be deduced, but reflectivity loss saturation is not yet attained at such a high level of damage. If the measured degradation rate can be assumed to be constant since the mirror was put into vacuum, we think on the basis of our experience in alignment operation that sufficient time will be available to complete alignment operations before mirror losses overcome gain.

References

[1] R. Barbini et al., J. de Phys. 44, C1 (1983) 1;
M. Castellano et al., Nuovo Cim. 81B (1984) 67;
M. Biagini et al., SPIE 453 (1985) 275.

[2] M. Ambrosio et al., INFN/TC-84/9 (1984);
M. Biagini et al., Nucl. Instr. and Meth. A237 (1985) 273;
M. Ambrosio et al., Nucl. Instr. and Meth. A246 (1986) 63.

[3] R. Barbini, M. Serio, F. Tazzioli and G. Vignola, Frascati internal report LNF-81/70 (1981).

[4] P. Elleaume et al., Appl. Opt., to be published.
D.A.G. Deacon, Nucl. Instr. and Meth. A250 (1986) 283.

[5] M. Ambrosio et al., Nucl. Instr. and Meth. A250 (1986) 289.