IMPROVEMENT AND RECENT RESULTS OF THE DELTA STORAGE RING FEL

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Abstract

Several modifications to the storage ring FEL at DELTA have been conducted in order to enhance speed and reproducibility of mirror alignment as well as flexibility of electron beam settings. We present the new hardware design and recent experimental results at a laser wavelength of 470 nm. Lasing was achieved with different filling patterns. By modulating the accelerating RF the laser macropulses can be forced into a Q-switch mode, varying between roughly 10 and 250 Hz without significant loss of outcoupled average power. Adaptation of the laser pulse intensity to the spontaneous undulator radiation intensity allows for simultaneous analysis of electron beam and laser pulse with a streak camera and allows the study of correlations.

MOTIVATION

The DELTA storage ring features a planar electromagnetic undulator (U250) consisting of 17 periods of 250 mm length in its northern straight section. It serves as optical klystron for a storage ring FEL at electron energies around 550 MeV. The first laser operation in the visible had been achieved in 1999 [1].

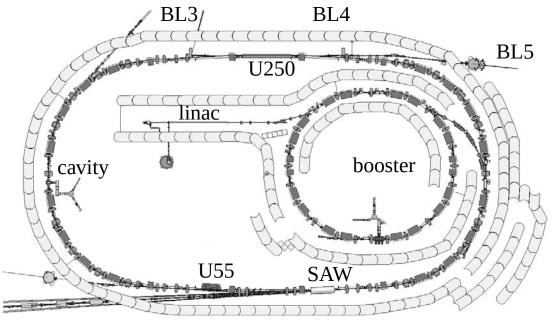

Figure 1: Overview of the DELTA accelerator complex.

Stable and easily reproducable laser operation at a wavelength of 470 nm has been established since fall 2007, mainly due to the construction and commissioning of new mirror chambers for the optical cavity.

NEW MIRROR CHAMBERS

Designed and built inhouse, the primary goal of the new mirror chambers was to significantly speed up the alignment process of the optical cavity, to improve its reproducibility and to allow fast mirror changes to switch between different laser wavelengths.

General Layout

Unlike the original layout, which was based on a 3-point control of the mirrors via piezoelectric actuators inside the vacuum chamber, the new design has the following basic advantages:

- fully separated axes
- actuators outside of UHV
- stepper motors and position encoders for better reproducibility of the alignment
- mirror holders support 3 mirrors each
- optional water cooling of the downstream mirror allows possible lasing at higher electron beam energies

Figure 2 shows the front view of the new upstream mirror chamber (engineering drawing). The complete chamber can be rotated around the vertical axis (yaw) and tilted over the pitch axis. The mirror holder is rigidly coupled with the chamber; only its relative vertical position can be changed, to quickly switch between the three available mirror slots. In addition to these three remote-controlled axes, the total length of the optical resonator is aligned by moving the downstream chamber along the laser axis with a stepper motor.

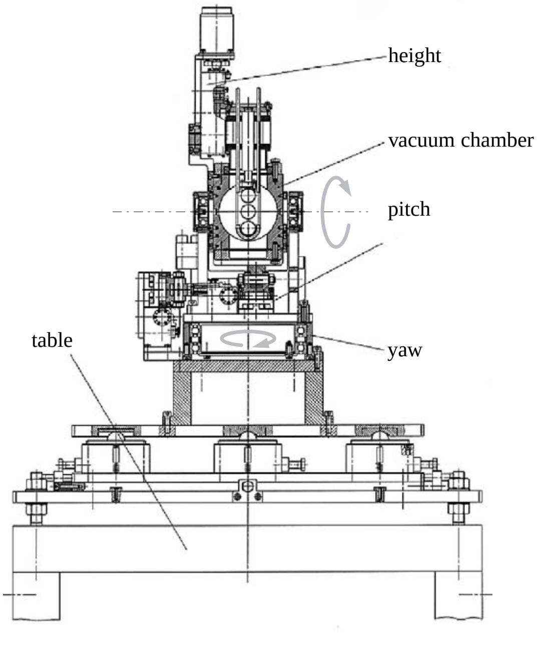

Figure 2: Mirror chamber (upstream).

Accuracy of Alignment

The achieved angular accuracy, dominated by mechanical hysteresis rather than step motor resolution (1.9 μrad), is better than 5 μrad for the pitch and yaw axis. Lasing at moderate beam currents below 10 mA was established with angular misalignments of up to ± 50 μrad. CCD-cameras aimed at the upstream and downstream beamshutters on the inside of the shielding wall allow for diagnostics of the transverse and angular alignment as well as for observing laser operation in frequent-injection [2] mode.

The length of the optical cavity (14.4 m, 1/8 of the storage ring circumference) can be varied with a reproducibility of 20 μm (2 μm step motor resolution), corresponding to a RF detuning of 700 Hz. Laser activity was observed within a frequency range of ± 200 Hz around perfect synchronicity between electron revolution and cavity length. Longitudinal prealignment using a streak camera[1] is possible with an accuracy of 500 Hz.

FEL PERFORMANCE

Beam Current

At 550 MeV, single bunch currents of up to 20 mA could be accumulated. During FEL shifts the current was limited by both the Touschek effect and a temporarily low vacuum lifetime to 10-15 mA.

Optical Cavity

Mirror[2] reflectivity at 470 nm, determined by measuring the half-life of stored light after dumping the electron beam, was 99.63%. This is in good agreement with old results [6], showing that neither several shifts of laser operation nor seven years of storing caused a measurable mirror degradation.

Gain

The initial FEL gain at the laser threshold current of roughly 3 mA just compensates for the cavity losses. The resulting gain value of 3% is in good agreement with the theoretical prediction of the low-gain model:

$$G_{0,\mathrm{ok}} = 7.4 \left(\frac{N_\mathrm{ok}}{N_\mathrm{u}}\right)^3 \left(\frac{N_\mathrm{ok}+N_\mathrm{d}}{N_\mathrm{ok}}\right) f_\mathrm{ok} G_{0,\mathrm{u}}$$

with the modulation depth f_ok of the optical klystron ($N_\mathrm{ok} = 7$) and the maximum gain $G_{0,\mathrm{u}}$ (see for example [9]) of a pure undulator ($N_\mathrm{u} = 17$).

FEL Power

By using a portable power meter (FieldMate, Coherent) with semiconductor sensor it was possible to measure the outcoupled laser power, averaged over 50 ms, during frequent-injection [2] operation. Results of an operational period of 7 hours are shown in figure 3. At a beam current of 14 mA the maximum power of 2.8 mW ($\pm 5\%$ calibration uncertainty) was observed.

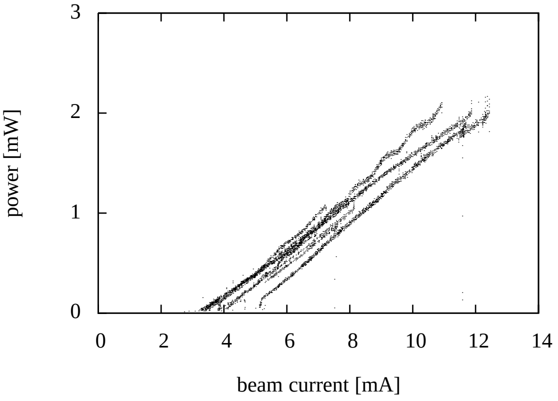

Figure 3: Average outcoupled FEL power.

Empirically the average outcoupled power P is roughly proportional to the average beam current, hence to the total synchrotron radiation power P_sr as well, in accordance with the Renieri limit. The quantitative evaluation of the Renieri limit [3, 4] can be written as

$$P = 8\pi \frac{T}{L}(N+N_d) f_\mathrm{ok} \left[\left(\frac{\sigma_\gamma}{\gamma}\right)^2_{on} - \left(\frac{\sigma_\gamma}{\gamma}\right)^2_{off} \right] P_\mathrm{sr}. \tag{1}$$

with the mirror transmission T, the total losses of the optical cavity L, and the relative energy spread with and without laser activity $(\sigma_\gamma/\gamma)_{on/off}$. The total synchrotron radiation power at 550 MeV, emitted from bending magnets and undulator, adds up to 2.25 W/mA. Equation (1) could up to now only explain the experimental results for beam currents close to the laser threshold. At higher currents the measured power is significantly larger than the predicted values; however the latter are highly uncertain, partly due to the unknown behaviour of transverse beam dimensions at high currents (which directly influence the gain and thus the laser-on energy spread in eq.(1)), partly due to the uncertainty of measured energy spread without laser activity (see [5]). Even when using the energy spread unperturbed by turbulent bunch legthening as laser-off value in eq.(1), as was proposed in [3], the experimental results are still underestimated in the case of DELTA.

Temporal Structure

Unlike the 50 Hz quasi-c.w. mode (induced by a power supply) observed in 1999 [1], the spacing between laser macropulses at beam currents of approx. 10 mA was consistently around 4 ms. The spacing shifted with decreasing beam current. This suggests that the FEL operates with the

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[1] *Hamamatsu C5680*

[2] dielectrical multi-layers on SiO_2 substrate, 50 nm bandwidth

Table 1: Parameters

laser wavelength	470 nm
K-value	2.54
$N + N_d$	85
electron energy	542 MeV
filling pattern	single bunch
laser threshold	3 mA
threshold gain	3 %
mirror reflectivity	99.63%
mirror transmission	$\approx 0.04\%$
outcoupled average power	< 3 mW
intra-cavity peak power	≈ 35 MW

theoretical, natural oscillation frequency [7, 8]

$$f_r = \frac{1}{\pi\sqrt{2\tau_0\tau_{\mathrm{s}}}} \tag{2}$$

with $\tau_0 = T_0/(G - L)$, bunch spacing $T_0 = 384$ ns, and damping time $\tau_{\mathrm{s}} = 90$ ms. By inserting the observed frequency of 250 Hz into eq.(2) one obtains an estimate for the gain G at high beam currents of roughly 8%.

The laser micropulse length, measured with a streak camera, is approx. 7 ps. This translates into an outcoupled peak laser power of 14 kW and an intra-cavity peak power of 35 MW.

By modulating the frequency of the accelerating RF (499.84 MHz) with an amplitude of up to 2 kHz and a modulation frequency between 10 Hz and 250 Hz, thus periodically varying the orbit length, it is possible to force the laser macropulses into a Q-switch mode with the corresponding frequency. Within the mentioned frequency range we observed no measurable change of the outcoupled average laser power.

Laser - Electron Beam Interaction

A streak camera is located at the end of the downstream undulator beamline, to observe the spontaneous undulator radiation as well as the outcoupled laser light. Using an additional resonator mirror with a low transmission ($\approx 0.04\%$) for the high intensity laser pulses allows for the simultaneous analysis of laser and electron bunch [9].

Figure 4 shows a series of laser macropulses with the optical cavity slightly detuned. The laser pulses migrate along the electron bunch. It is worth noticing that the next laser pulse already starts growing while the former one has not yet decayed completely.

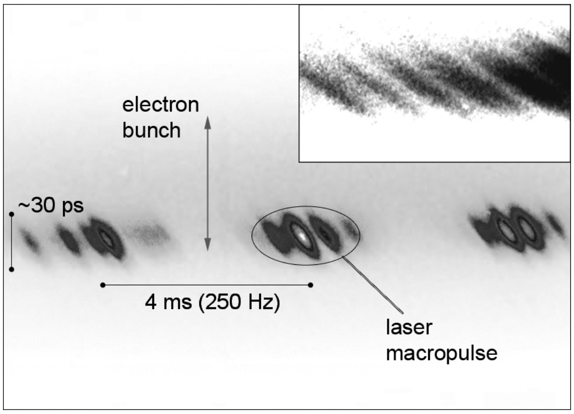

Figure 4: Double sweep streak camera image of laser pulses ($\sigma_{t,\mathrm{fel}} = 7$ ps) migrating over the electron bunch ($\sigma_{t,\mathrm{e}} \approx 40$ ps).

FEL operation was also established in few-bunch mode (i.e. a bunch train of 5-10 buckets filled) and in 4-bunch mode (one bunch per stored light roundtrip), despite the lack of a longitudinal feedback system to counteract coupled-bunch instabilities. Due to strong synchrotron oscillations however, laser macropulses showed up in random fashion (approx. one per second). The laser threshold current in 4-bunch mode was slightly lower than 1 mA per bunch, in accordance with the measured cavity losses and threshold current in single bunch mode.

CONCLUSIONS

New FEL mirror chambers were installed into the DELTA storage ring. The designated accuracy and reproducibility of alignment was achieved, significantly speeding up switching between standard user and FEL operation. Lasing was achieved with different filling patterns. For low to medium beam currents the measured outcoupled power and gain is consistent with the theoretical predictions of the low-gain model and the Renieri limit. The average power did not decrease in Q-switch mode for frequencies down to 10 Hz, which corresponds to the synchrotron damping time. Laser light and electron bunch could be simultaneously analysed with a streak camera, showing the macropulse generation.

ACKNOWLEDGEMENTS

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