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Celeroton White Paper

Optical switches based on high-speed magnetic bearing motors

Table of Contents

1 Application / Introduction

A number of emerging applications ask for a dramatically improved performance of femtosecond laser systems concerning pulse energy. Due to limitations in the amplifier medium, further improvements within the laser source are increasingly challenging. Stacking of multiple amplified pulses via methods such as Stack-and-Dump seems to be a possible solution [1] . As shown in Figure 4, a passive optical resonator is used to stack a large number of laser pulses arriving with a high repetition rate (multi-MHz) in order to create high-energy pulses at lower repetition rates (multi-kHz). To extract these high-energy pulses, a fast, efficient, minimal-invasive switch is necessary. State of the art switches make use of electro-optic or acousto-optic effects but their transmissive nature limits the achievable energy due to nonlinear effects or damage [2] . Finding a suitable switch remains a puzzling task and only recently a promising new approach employing small fast rotating mirrors as a dumping device in order to extract energy from the cavity was theoretically proposed and thoroughly described [3] .

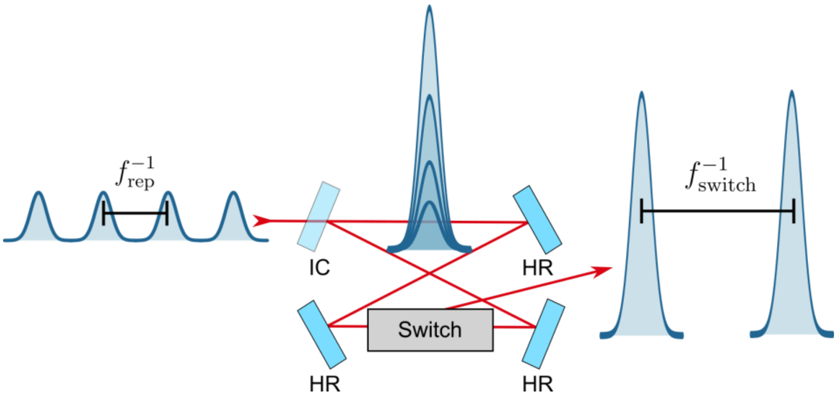

Figure 1: Concept of a stack-and-dump enhancement cavity.

2 Mechanical switch based on rotating motor

The concept of such a switch based on fast rotating mirrors is shown in Figure 2. The rotor is employed to map the beam inside the cavity on a different position along a circular pattern at each roundtrip to allow the extraction of only the desired one using a small mirror segment.

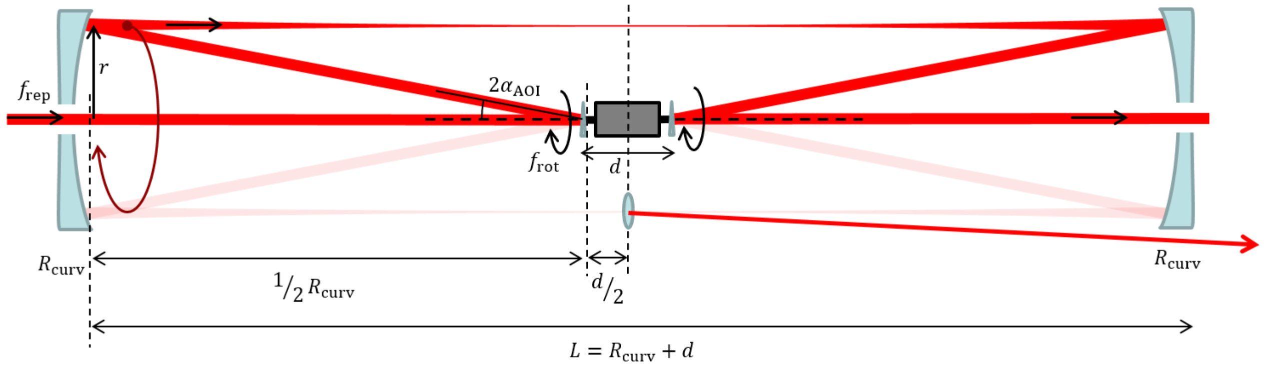

Figure 2: Concept and basic parameters of a mechanical rotor employed as an optical switch in an enhancement cavity.

N: # Pulse within one rotational period	$N = \frac{f_{rep}}{f_{rot}}$	$r = \frac{(L-d)}{2}\tan(2\alpha_{AOI})$
Δs: distance between sequent pulses	$\Delta s = \frac{2\pi r}{N}$	$\Delta s = \pi(L-d)\tan(2\alpha_{AOI})\frac{f_{rot}}{f_{rep}}$
α_{AOI}: angle of incidence (polarisation, astigmatism)	➔ Required rotational frequency: **~5 kHz** (300,000 rpm)	

The mirrors, and therefore the mechanical rotor requires high and extremely stable velocities and needs to be operated in vacuum due to the high laser power. Furthermore a high pointing stability is demanded to minimize deviations of the beam within the cavity. These requirements can only be fulfilled by a high-speed magnetic bearing motor. However a magnetic bearing motor which can fulfill the velocity stability and the rotor-displacement requirements has not yet been shown. Hence, a modified Celeroton CM-AMB-400 was thoroughly investigated in collaboration between Celeroton, the Institute of Applied Physics in Jena and the Max-Planck-Institute for Quantum Optics in Garching near Munich.

3 Measurements with Celeroton CM-AMB-400

In this section, a brief explanation of the measurement setup and the results is given. Further details can be found in [5] .

3.1 Measurement setup

The motor, which is used for the measurements, is the Celeroton magnetic bearing motor CM-AMB-400. The motor consists of two active magnetic radial bearings, an active magnetic axial bearing and the motor drive integrated into a heteropolar motor and a homopolar motor, allowing for a rotor with a load in the axial center of the motor.
The rotor sleeve is made of titanium and contains one radially magnetized permanent magnet (PM) for the first radial bearing and the motor drive and two axially magnetized PMs for the second radial bearing and the axial bearing [6] . For the purpose of the measurements presented herein, the motor is equipped with a customized rotor with a triangular shaped mirror located in the axial center of the rotor. One plane of the mirror has a polished surface in order to enable the reflection of a laser beam (Figure 3). The motor torque is generated with pulse width modulation (PWM) below the synchronization frequency and with pulse amplitude modulation (PAM) above the synchronization frequency. The synchronization frequency is set to 333 Hz for measurements in air and to 666 Hz for measurements in vacuum.

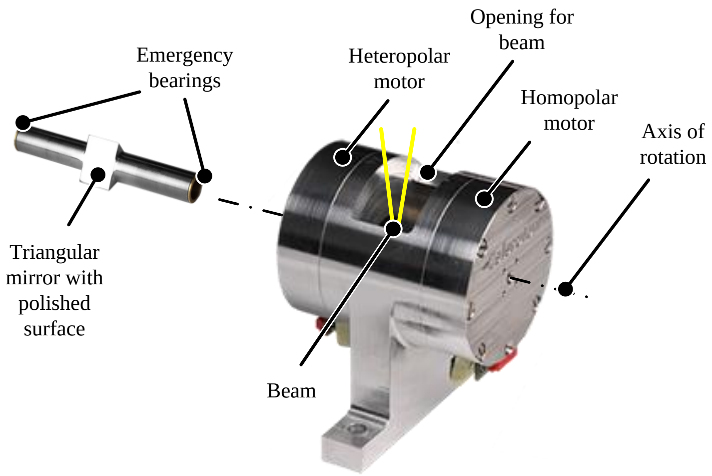

Figure 3: Employed rotor (left) and entire magnetic bearing motor CM-AMB-400 (right). One of the three surfaces of the rotor mirror is polished in order to deliver a laser reflex that suffices the requerements of the measurements.

For the pointing error measurements, a high-speed-camera captures the spatial beam displacement perpendicular to the optical axis and parallel to the rotation axis (see Figure 4). This allows to monitor the angular deviations of the rotor position between the roundtrips.

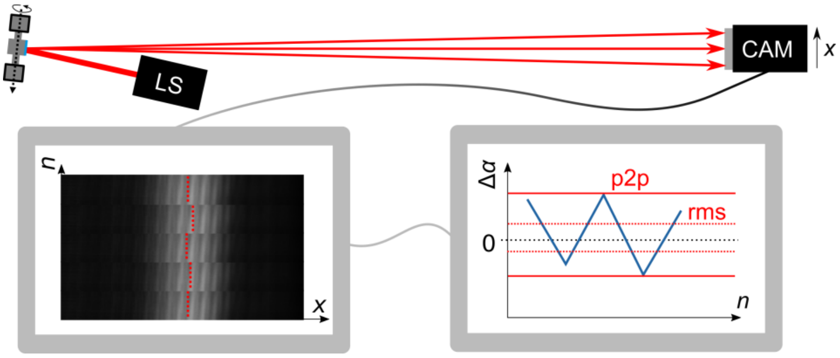

Figure 4: Setup to measure the pointing errors.

Figure 5 shows the measurement setup for the velocity error measurements including a photo diode to record time differences between laser pulses accurately. For practical reasons the terms 'jitter' and 'drift' are defined as follows (see Figure 5). Drift is the moving average over 10 subsequent roundtrip-time deviations. RMS drift is the RMS-deviation of this drift from the mean revolution time. In many optical applications, drifts can be actively compensated for. RMS jitter is defined as the RMS-deviation of the measured Δt from its drift and can typically not be compensated for.

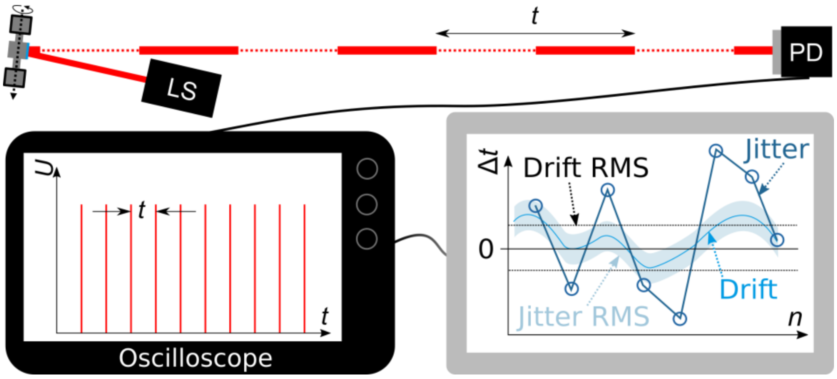

Figure 5: Setup to measure the velocity errors.

3.2 Measurement results

Figure 6 shows the offsets of the average angles for each rotation frequency together with error bars illustrating the RMS and peak-to-peak deviations of the individual traces. The offset, as well as the RMS- and p2p-deviation, are notably smaller for the vacuum measurements. This is, similar to the temporal jitter, most likely caused by air fluctuations which disturb the rotor. The deviations are drastically reduced from 1 kHz to 2 kHz. In the bearing control the position measurements are filtered with a notch filter with a corner frequency equal to the rotational speed. This notch filter is enabled for speeds higher than 1 kHz and therefore explains the reduction in the angular deviations. At 5 kHz, the pointing fluctuated by 12 µrad (RMS) and 33 µrad (peak-to-peak) over ~10,000 round-trips.

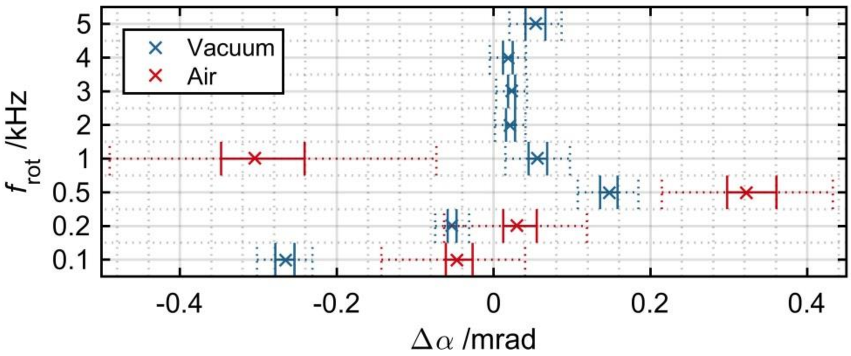

Figure 6: Constant offset of the pointing angle and the RMS- and p2p-deviation depending on the rotation frequency for the measurements in vacuum and air.

Figure 7a depicts the overview of the measurements for different rotation frequencies. At each frequency a multitude of measurements with activated and deactivated motor drive were carried out, examples are shown in Figure 7b, c and d. The large difference of the results with the activated and deactivated motor suggest that both jitter and drift in vacuum are mainly caused by the driving motor, while the contribution of the bearing is negligible. With active motor drive, the fluctuation in most vacuum measurements at all rotation velocities is dominated by a modulation as illustrated in Figure 7c. Most likely, this is due to the control loop of the rotor velocity. So far, the velocity controller is implemented in fix point arithmetic, and therefore the rounding error might cause this slow modulation. This effect is unexpected but might be get rid of with floating point arithmetic. To summarize: the acquired data allows to identify the rotor drive as the main source of velocity variations with fast fluctuations of up to 3.4 ns (RMS) and slow drifts of 23 ns (RMS) over ~120 revolutions at 5 kHz in vacuum.

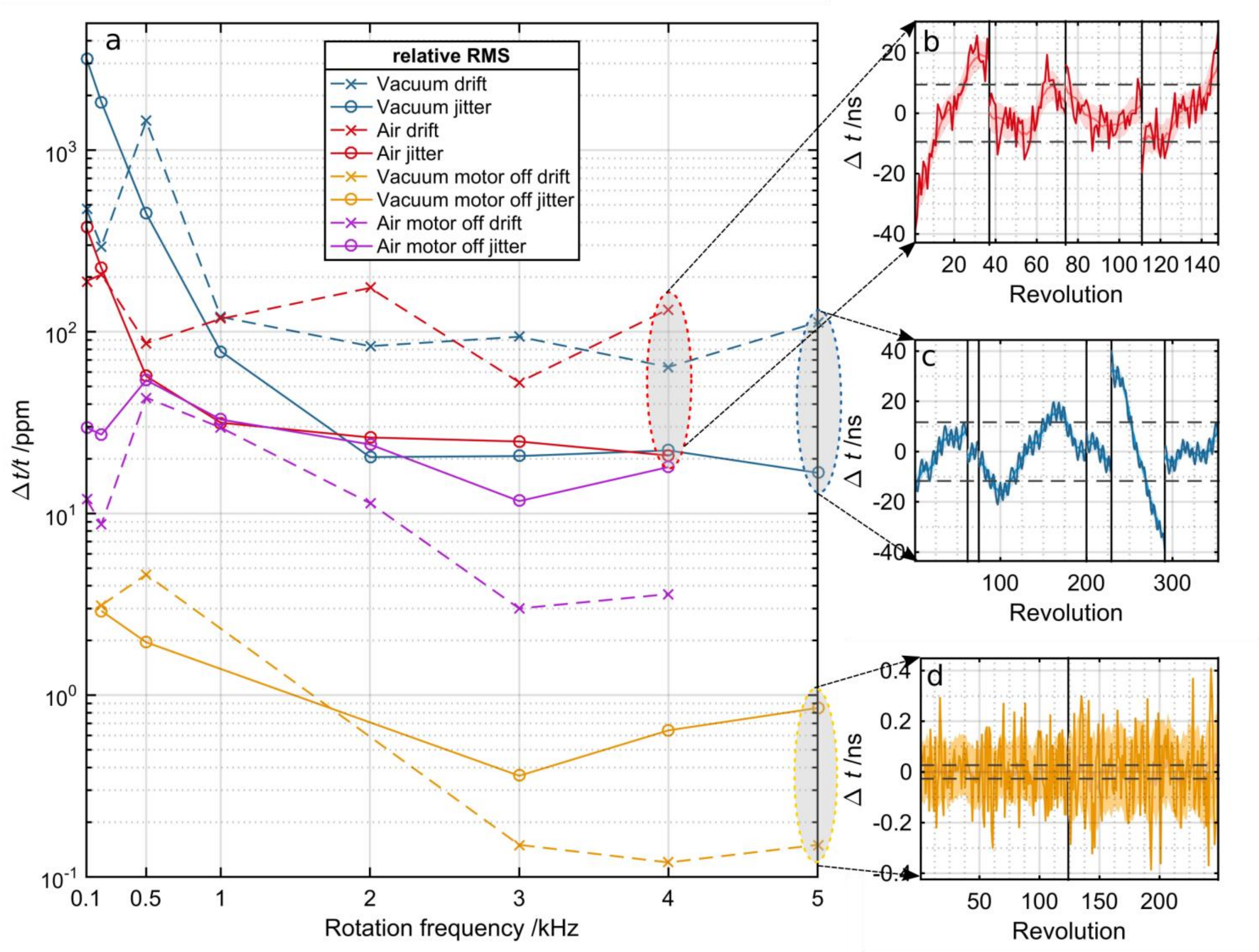

Figure 7 a) Overview of maximum relative drift RMS and maximum relative jitter RMS for all acquired rotation frequencies in air (red), vacuum (blue), in vacuum with deactivated driver (yellow) and in air with deactivated rotor (purple). (Connecting lines between measurement points were only added to improve visibility and represent no experimental data) b) All traces of the measurements in air at 4 kHz rotation frequency (5 kHz could not be measured in air). c) All traces of the measurements in vacuum at 5 kHz rotation frequency. d) All traces of the measurements in vacuum at 5 kHz rotation frequency with deactivated motor, ring-down slope removed. The individual traces are visually separated by black lines in the plot.

4 Outlook

The measurements undertaken with a modified CM-AMB-400 show that magnetic bearing motors could be a feasible solution for mechanical switches as crucial part of an enhancement cavity setup for performance increase in femtosecond laser systems, while still offering significant potential for optimization. A next step could be a customized magnetic bearing motor design with a rotor with two end mirrors in order to test magnetic bearing and finally the optical switch performance in an experimental setup.

5 Similar applications

- Application examples of the magnetic bearing CM-AMB-400 motor for optical applications: https://www.celeroton.com/en/technology/tech-blog/detail/application-examples-of-the-magnetic-bearing-cm-amb-400-motor-for-optical-applications.html
- 500,000 rpm rotational speed thanks to magnetic bearings: https://www.celeroton.com/fileadmin/user_upload/medien/201412_Celeroton_Magnetic_Bearing_EN.pdf
- A high-speed motor for satellites: https://www.ethz.ch/en/news-and-events/eth-news/news/2016/07/high-speed-motor-for-satellites.html

6 Appendix

6.1 About the Research-Project: ACOPS

The research group Fiber & Waveguide Lasers at the Institute of Applied Physics (IAP) is part of the Friedrich-Schiller University in Jena (Germany) and is working on the development of new concepts for solid-state lasers such as fiber lasers, pulse shaping and fiber-optical intensification of ultrashort laser pulses. Research at the Max-Planck-Institute of Quantum Optics (MPQ) in Garching (Germany) concentrates on the interaction of light and matter under extreme conditions. Together, they are currently working on the EU-funded project ACOPS (Advanced Coherent Ultrafast Laser Pulse Stacking), which focusses on the implementation of enhancement cavities as devices to increase the energy of ultrashort laser pulses [7] .

6.2 About Celeroton

The Swiss high-tech company Celeroton AG (www.celeroton.com) is the leading manufacturer of ultra-high-speed electrical drive systems and turbo compressors with speeds up to 1 million rpm.

Faster, smaller, lighter and more efficient: Celeroton‘s turbo compressors, converters and permanent-magnet motors are designed for the highest energy efficiency at the lowest volume and weight. Their innovation lies in the interdisciplinary know-how in the areas of aerodynamics, gas and magnetic bearings, mechanics, electromagnetics, electronics, control systems and software that allows for outstanding solutions in terms of compact size, efficiency and control performance.

Application areas of the turbo compressors include air supply systems for fuel cells, air conditioning and heat pumps, high-tech blowers, respirators and oxygen concentrators and decentralized pneumatics. The motors and converters are applied in the medical and dental industry, in spindles for micromachining, and to drive rotating mirrors and prisms in optical systems, lasers and scanners.

6.3 References

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[6] C. Zwyssig, T. Baumgartner, J. W. Kolar, “High-Speed Magnetically Levitated Reaction Wheel Demonstrator,” Int. Pow. Electron. Conf. (IPEC – ECCE Asia), 1707-1714, 2014
[7] http://cordis.europa.eu/project/rcn/111552_en.html