Eur. Phys. J. AP **20**, 183–190 (2002)
DOI: 10.1051/epjap:2002090

The European Physical Journal
Applied Physics

Teramobile: A mobile femtosecond-terawatt laser and detection system

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Received: 10 December 2001 / Received in final form: 29 January 2002 / Accepted: 18 February 2002
Published online: 15 November 2002 –

Abstract. We describe the Teramobile system, a new mobile femtosecond multi-terawatt laser and detection system based on a state-of-the art CPA laser system embedded in a standard freight container, as well as a mobile detection unit allowing a characterization of the nonlinear propagation of high power laser pulses over long horizontal distances. The unique mobility feature of the whole system opens the way to previously unreachable applications for high-power laser pulses in the field of atmospheric research (lidar, laser-triggered lightning), which are also briefly reviewed.

PACS. 42.60.By Design of specific laser systems – 42.65.-k Nonlinear optics – 42.68.Wt Remote sensing: LIDAR and adaptive systems

1 Introduction

The interest in nonlinear pulse propagation has been significantly renewed since 1985, when the development of the chirped pulse amplification (CPA) technique [1,2] permitted to produce ultra-short laser pulses which now reach powers in excess of 10^{14} W. At those power levels, nonlinear phenomena dominate pulse propagation even in diluted media such as atmospheric pressure gases, opening the way to applications in atmospheric research. However, current high-power lasers are restricted to laboratory experiments due to their size and delicate operation. For the first time we developed a mobile laboratory hosting a CPA fs-TW laser system as well as detection and analysis tools.

In the following, we shall briefly describe relevant properties of nonlinear propagation of ultra-intense pulses in air, showing the need for a mobile high-power laser system. The subsequent section will be dedicated to a detailed description the main components of the Teramobile system: the laser system, the container laboratory and the mobile diagnostics unit. The last section is dedicated to a review of some of the applications as well as the first results obtained by the Teramobile team with our unique tool in its first months of life.

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Nonlinear self-action leads to strong modifications of the spatial [3–5], spectral [6,7] and temporal [8–11] characteristics of the pulse. The propagation medium is also affected. It undergoes multiphoton ionization and plasma production [12–15]. One of the most spectacular processes under such conditions is filamentation, which mechanism is described *e.g.* in [16]. Briefly, a dynamical equilibrium between self-focusing due to the Kerr effect and ionization of air leads to a defocusing effect. This equilibrium results in a self-trapping of the beam lasting for a distance of at least 200 m, *i.e.* much longer than the Rayleigh length [17,18], with a diameter reported to be about 100 μm [4,19]. In those filaments, the intensity reaches 10^{13}–10^{14} W/cm^2 [20], sufficient to generate significant self-phase modulation (SPM), yielding a bright white light supercontinuum [21]. However, the propagation properties of high-power laser pulses over long distances is still unknown. Up to now, the filamentation has been mainly studied in the laboratory over a maximum distance of several tens of meters. Measurements over km-range paths require field experiments, while theoretical simulations, even over distances of one meter, require unreasonable computing time at present.

Recently, interest in long-range propagation of fs-pulses was strongly enhanced when Rairoux *et al.* demonstrated a supercontinuum-based multispectral lidar

(Light Detection and Ranging) technique [22,23]. Emitting fs-TW laser pulses in the atmosphere and collecting the backscattered white light, they detected a supercontinuum signal from distances up to 13 km, opening the way to a multi-wavelength atmospheric remote sensing. Since the white light supercontinuum covers the whole visible and near-IR range up to 4 μm [24], it might permit to detect many constituents of the earth atmosphere.

Besides lidar, the broadband supercontinuum generation may be used to excite multiwavelength guide stars, which are needed to correct the large-scale inhomogeneities of the atmosphere at large astronomical telescopes using adaptive optics [25]. Other applications are based on the ionization induced in the air by the self-guided high-power pulses. The plasma channels behave as conducting wires. High power lasers may therefore trigger lightning [26–29]. Also, it is well known that ions can act as condensation nuclei [30], which could lead to laser-triggered rain nucleation in over-saturated atmospheres.

Hence, the need for a femtosecond-terawatt laser system suited for field experiments emerged. For the first time, we developed a fully standalone multi-terawatt laser system, based on a fs-TW laser system integrated in a mobile laboratory built in a standard-dimensioned sea container. This mobile laboratory provides the necessary infrastructure for the laser system as well as the sending and the receiving optics and the detection electronics for lidar. It is supplemented by a mobile beam characterization unit, which is itself a second standalone optics laboratory constructed in a trailer. This infrastructure is obviously suited for km-range propagation experiments, since the mobile system can be installed on long horizontal spots such as the runway of an airfield, permitting to study the beam continuously along its propagation path with the characterization unit.

The mobility also has the big advantage to allow further evaluation of the potential of fs-TW pulses for specific applications or experiments, without permanently installing an expensive and complex system at the place of interest. For example, short test experiments at large facilities such as synchrotrons are made possible at a reasonable investment.

2 The Teramobile system

The Teramobile laser is the first mobile femtosecond-terawatt laser system. This unique mobility feature imposed a particularly compact design for the laser. The environmental requirements of such a system determined the conception of a mobile standalone laboratory, including all the sending and receiving optics as well as diagnostics and detection systems. The system as a whole was designed as a versatile tool intended for fundamental as well as atmospheric applied research, and finally as an open system for further improvements of experiments in other scientific fields.

Table 1. Laser characteristics.

Center wavelength	793 nm
Bandwidth	16 nm
Pulse energy	350 mJ
Pulse duration	70 fs sech^2
Peak power	5 TW
Repetition rate	10 Hz
Output beam diameter	50 mm
Chirped pulse duration adjustment	70 fs to 2 ps, positive or negative chirp
Energy stability	2.5% RMS over 400 shots
Dimensions	3.5 × 2.2 m

2.1 Laser system

2.1.1 Laser setup

The Teramobile laser is based on the well-known chirped pulse amplification (CPA) technique [1,2]. However, its integration in the reduced space of the mobile laboratory required a particularly compact design, which was developed in cooperation with Thales Laser (formerly BMI division, Thomson CSF, Orsay, France). Its main characteristics are summarized in Table 1. Briefly, the system consists of a compact Ti:Sapphire oscillator (Compact Pro, Femtosource, Vienna, Austria) and a Nd:YAG pumped Ti:Sapphire amplification chain including a regenerative amplifier and two 4-pass amplifiers. A T-shaped table yielded an optimal compactness together with a reasonable access to the system for alignment and operation. The laser can be monitored with the usual diagnostics installed in a rack fixed above the laser table (Fig. 1). Spare space has been reserved for diagnostics to be made available in the future, either permanently or for a specific experiment.

2.1.2 Compensation of the group velocity dispersion

Since atmospheric applications imply the propagation of ultrashort laser pulses over long distances in the atmosphere, group velocity dispersion (GVD) has to be taken into account. In the first order, GVD results in the temporal broadening of the laser pulse, stretching our 70 fs long, 16 nm broad pulse into a strongly chirped, 1 ps long pulse with a 10-fold reduced peak power after 1 km propagation. However, it was shown [22,31] that a negatively chirped pulse is temporally recompressed by GVD, leading to an ultrashort pulse after a propagation distance depending on the initial chirp (Fig. 2). To perform this precompensation of the GVD, we installed one of the compressor gratings on a long-course (40 mm) motorized translation stage. Its translation yields a pulse stretching of 43 fs per mm detuning, hence allowing to precompensate the GVD in up to 1.5 km of air. Further compensation as well as the compensation for higher order dispersion can be provided using a pulse shape modulator.

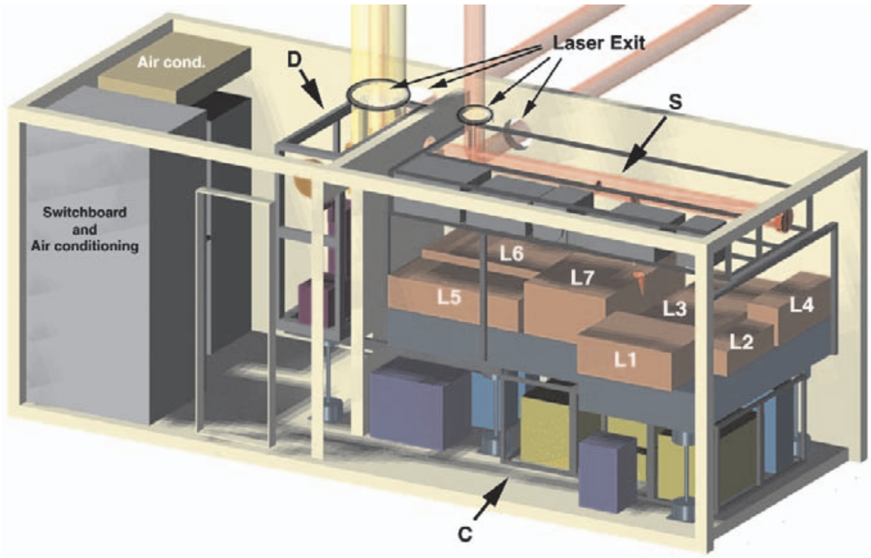

Fig. 1. Three-dimensional view inside the Container. The beam expanding system (S) (see also Fig. 3), controllers and power supplies for the laser system are installed on the rack mounted on top of the laser table. The laser system is composed of an oscillator (Femtosource) with a YAG pump laser (Verdi) (L1), a stretcher (L2), regenerative amplifier, multipass preamplifier (L3) and their Compact YAG pump laser (L4). A multipass main amplifier (L5) is pumped by two SAGA-YAG units (L6). The final part is the compressor (L7). The main power supplies of the laser system are installed together with a dedicated water-air heat exchanger in a closed isolation box under the table (C). Details of the Teramobile Detection (D) are shown in Figure 4.

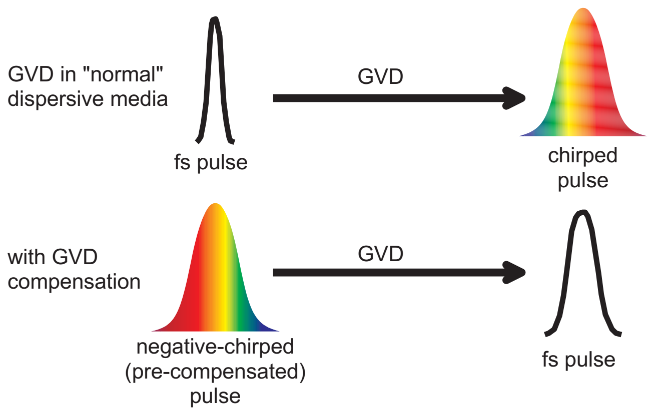

Fig. 2. Principle of the compensation of the group velocity dispersion.

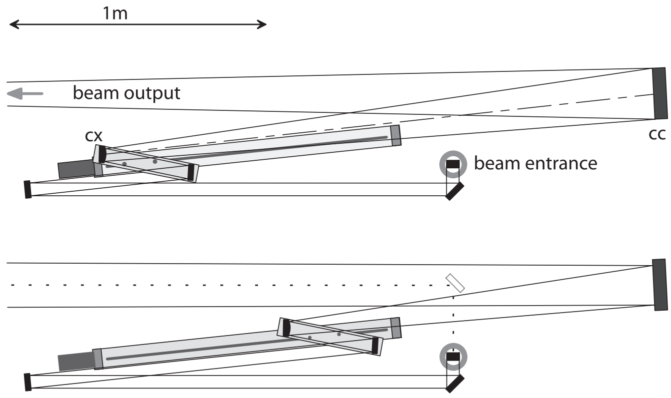

Fig. 3. Variable off-axis sending telescope. Up: setting for strongest focus (<10 m). cx: 75 mm convex mirror, cc: 200 mm concave mirror; – - – indicates the optical axis between the spherical mirrors giving the translation path. Down: setting for slight divergence; - - - indicates the direct sending option bypassing the telescope.

2.1.3 Sending optics system

Besides transporting the beam directly to the output windows of the mobile laboratory, the sending optics permits to vary its beam diameter and focus. The beam diameter has a critical influence on the distance at which filamentation will occur. Expanding the beam, and hence reducing its intensity, can be favorable to prevent unwanted self-focusing after short distances of propagation through air, which would damage the output windows or sending mirrors. Moreover, controlling the initial focus or divergence of the beam is a key parameter to study the propagation of ultrashort laser pulses as well as to control the filamentation distance.

The geometrical control of the beam is achieved by an off-axis sending telescope (Fig. 3 and Tab. 2) based only on reflective optics with dielectric coatings, to preserve the temporal and spectral pulse characteristics. To keep the aberration negligible, the telescope extends over the whole available length in the mobile laboratory. It is installed in a rack which is rigidly attached above the laser system (Fig. 1 (S)). The special Z-geometry of the optical path permits to set the focal length of the telescope with a single translation stage (isel automation). The telescope can also be by-passed to use the original 5 cm beam diameter of the laser. The beam can be sent either horizontally to continuously characterize its propagation over long distances, or vertically, *e.g.* for lidar measurements.

Table 2. Sending telescope characteristics.

Focal length	10 m to slightly divergent
Magnification	2.7
Output beam diameter	15 cm
Pointing stability	0.1 mrad over the whole focusing range
Off-axis angle	6°
Length	2.5 m
Translation stage precision	12.5 μm

Table 3. Mobile laboratory specifications.

External dimensions	Standard ISO 20 ft Container
Internal dimensions	5.70 m × 2.15 m × 2.20 m
Weight including equipment	10 tons
Power consumption during full operation	30 kW (380 V, 63 A, 3P connector)
Storage power connection	240 V, 16 A
Temperature stability (laser room)	±1 °C
Outer temperature range	−20 °C to +35 °C
Humidity range	0 to 100%
Sending, receiving ports	2 × ⌀25 cm, 2 × ⌀45 cm
Certificates	DIN, IEC, VDE, CEE, NEMKO, CSC

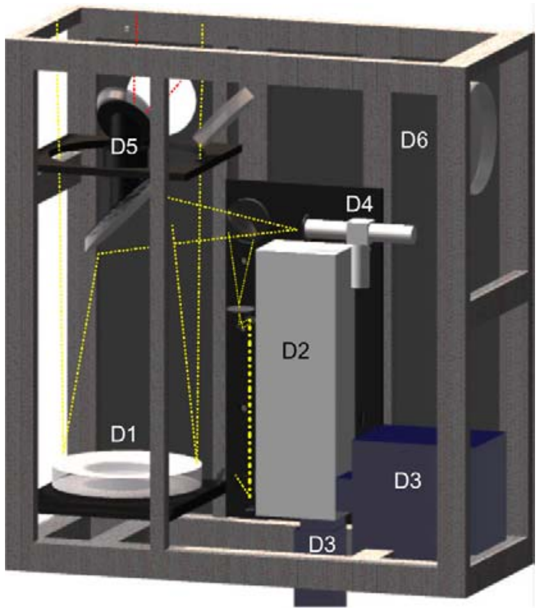

Fig. 4. Detection system: the detection system inside the container consists of a 40 cm receiving telescope for lidar measurements (D1), a 50 cm spectrograph (Chromex 500ism) mounted vertically (D2) with two outputs: ICCD (Princeton) and photomultiplier/avalanche photodiode (Hamamatsu/Licel) (D3), a second optical path to measure the depolarization (D4), the on-axis sending mirror (D5) and a horizontal telescope to follow the long-path horizontal propagation experiments (D6).

Moreover, the beam can also be emitted through the detection box to permit coaxial lidar experiments. Each of the 4 ports is equipped with a 2-D steering capability over ±10°, as well as the option to attach a full 3-D steering system to the frame of the windows on the roof or the outer wall of the mobile laboratory.

2.2 The mobile laboratory

The Teramobile laser system and its equipment are build in a standard sea container (see Tab. 3 for detailed specifications). Since TW-class laser systems are very sensitive to mechanical vibrations and shocks, the optical system as a whole (including the laser, sending and receiving optics) was designed as a single rigid unit smoothly linked to the outer structure of the container through special damping elements. This makes it possible to transport the system to virtually any place in the world and operate it provided climatic conditions permit the operation of the laser system.

The Teramobile mobile laboratory itself, as the infrastructure for the scientific equipment, was designed in a cooperation between the Freie Universität Berlin and Impres GmbH (Bremen, Germany) and was build by TSU (Bremerhaven, Germany). Figure 1 gives an overview of the main structure of the system. The mobile laboratory is divided into two rooms. The partition wall acts as a thermal insulation and electromagnetic shielding. The first room hosts the laser system including all the power supplies of the pump lasers, the driving electronics as well as the sending optics and the diagnostics systems (Fig. 4). The other room contains mainly the detection system, as well as most of the technical functions such as the power distribution, air conditioning devices, storage, control of water supplies. This room is also used as the control room during the experiments.

To ensure the stable operation of the femtosecond laser system, the temperature control is separated into three uncoupled volumes: (i) the control room which acts as an air lock, (ii) the laser room and (iii) a closed isolation box containing all the power supplies of the lasers, cooled by a dedicated water-air exchanger. Under reasonable outdoor conditions, the strongly dimensioned air conditioning even permits to remove the sending windows from their frame to avoid non-linear effects in their glass.

Eye-safety is always a key issue when dealing with lasers. Since a TW laser can not be eye-safe, a security system controls the operation of the laser. Hence, the laser can be blocked by a shutter which is controlled by suitable detectors according to the type of experiment, like a motion detector, hand controller, as well as an additional safety lidar, which are upgradeable to future applications.

2.3 Detection units

2.3.1 Detection system inside the container

The detection system inside the Teramobile (Fig. 4) is mainly designed to perform lidar measurements and can work in an off-axis or on-axis mode with respect to the emitted beam. The detection consists of a vertically mounted 40 cm receiving telescope and two detection channels. The first channel consists of a spectrograph for spectrally and temporally resolved measurements. The second one is used to measure depolarization for fundamental investigations of the white light generation and scattering in the filaments, as well as for atmospheric particles characterization. The unit also contains a horizontal telescope aimed at comparing the backscattered light to the forward emission detected by the mobile detection unit described in the next section. Both telescopes and both detection channels can be connected either directly or through fiber couplings. The wavelength range of the detection system ranges from 190 nm to 2.5 μm, using a spectrometer with three integrated gratings and four possible detectors (ICCD 190–950 nm, Hamamatsu PMT 350–1700 nm, Si APD: 700–1100 nm and InSb 1.5–2.5 μm). With interference filters and the depolarization path, the wavelength range may be extended up to 5 μm.

2.3.2 Mobile detection unit

In order to permit the characterization of the laser beam at an arbitrary and large distance, we developed a mobile characterization unit mounted inside a trailer, which can be moved continuously along the beam. It contains a stand-alone optics laboratory equipped with air conditioning, breadboard, desktop and its own power generator.

For safety reasons, since the mobile detection unit is placed inside the laser beam path, it has no window. The only input port is a sampling device, made of a diffuser and a collecting fiber, which can be scanned in two dimensions across the laser beam by a 1.5 m long articulated arm, remote controlled from the inside of the mobile unit. The trailer is also equipped with a screen and an attached video camera, to perform far-field imaging of cross-sections of the laser beam at various distances, up to several km. Since the trailer can be moved along the laser beam on a straight road or an airfield runway, it provides an axially resolved sampling of the beam propagation. Combined with the radial and angular move of the sampling device, this gives access to a full 3D characterization of the laser beam over its propagation path.

3 Applications and first results of the Teramobile system

3.1 Control of the filamentation distance

As pointed out in the introduction, atmospheric applications of the nonlinear propagation of ultrashort laser pulses rely on white-light continuum and plasma generation in self-guided filaments. Therefore, long range studies of the propagation of high-power laser pulses have to be performed to be able to understand and control the beam propagation, *e.g.* the filamentation distance.

The mobility of the Teramobile system permits such studies, for instance by installing the system at one end

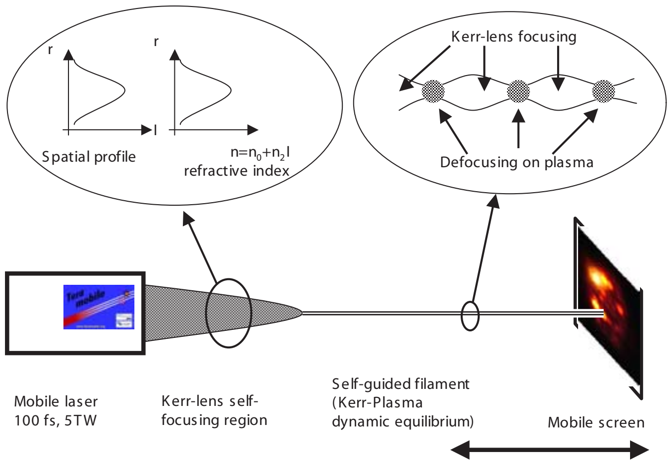

Fig. 5. Principle of filamentation and experimental setup to study the filamentation distance.

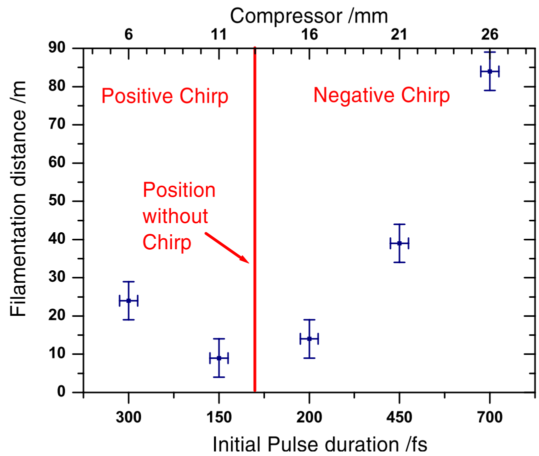

Fig. 6. Filamentation distance as a function of the laser chirp. Uncertainties are +/−10% for pulse duration and +/−5 m for the filamentation distance. Note that the horizontal axis is not linear. The minimum pulselength corresponds to approximately 100 fs.

of an airfield runway, and scanning along the beam with the mobile characterization unit. Here, we shall describe preliminary results about the formation and length of self-guided filaments obtained over 100 m distance, as a function of the initial chirp. In this experiment, pulses with 330 mJ energy and a minimum pulselength of 100 fs were emitted as a 5-cm diameter beam. The filament formation was observed as bright spots on a screen placed in the laser path (Fig. 5).

The high power of the Teramobile system (4 TW), much above the critical power $P_{\mathrm{crit}} = \lambda^2/(4\pi n_2) \approx 1$ GW, leads to multifilamentation of the laser beam. The filamentation distance, *i.e.* the distance between the output of the compressor and the beginning of the filaments, strongly varies with the initial chirp of the emitted pulse, as shown in Figure 6. Filamentation occurs much before the pulse is temporally recompressed by GVD. For example, a 16 nm broad pulses is only expanded by 1 ps/km in air by linear dispersion.

This can be understood considering that even with a strong chirp, the pulse power keeps much above the critical power, allowing self-focusing and filamentation to occur before the short pulse is temporally recombined at a remote location. Moreover, in a multi-filamentation regime, the dynamics of the filament formation strongly depends on the laser beam profile because filaments start at slight inhomogeneities of the beam profile. This shows the need to use an expanded and/or slightly divergent beam with a good control of the beam profile in order to further increase the filamentation distance. However, this experiment illustrates the possibility to control the filament distance by adjusting the laser parameters, which is a key issue for long-range atmospheric experiments.

3.2 Lidar

Lidar [32] is an efficient technique in atmospheric research. It permitted to understand many important atmospheric phenomena, such as the mechanism of stratospheric ozone depletion [33]. The main advantage of lidar over other remote sensing techniques – as DOAS [34], FTIR [35] or satellite based spectroscopy [36] – is the high range resolution over long distances, which is achieved by the use of short pulse laser (typically a few nanoseconds or less) and fast electronics to record the signal of the light backscattered by molecules and aerosols. However, the number of the detectable species is limited by the availability of narrow-lined pulsed laser sources at suitable wavelengths, especially in the IR. Moreover, since the laser has to be tuned on an absorption band of the species to be measured, only one molecule can be measured at once, and interference between molecules having overlapping spectra are difficult to correct.

Other techniques such as DOAS or FTIR overcome this limitation through a wide available spectral range, but at the cost of a range-integrated measurement. The use of the laser-generated white light continuum in a nonlinear lidar would combine the advantages of both techniques. White light pulses generated by laser-induced filaments in the sky should simultaneously provide range and spectral resolutions. Moreover, the supercontinuum emission covers the near- and mid-infrared [24], where many important pollutants, such as the volatile organic compounds (VOCs), have their absorption bands. Approaches which have been made in remote sensing of VOCs, *e.g.* to use broad bandwidth (dye) laser sources with FTIR detection [37] or to do DIAL with OPO lasers [38], have their limits in the tunability of the lasers or the spectral resolution. The latter is needed to be able to retrieve concentrations of trace gases, while their bands overlap and strongly interfere with absorption lines of water and CO_2.

The Teramobile could overcome some of those limits and provide a multi-component analysis, by implementing the first mobile white-light lidar system based on highly nonlinearly propagating pulses. Briefly, the TW laser beam is sent into the atmosphere, and the backscattered light is detected on a spectrometer-photomultiplier combination (Fig. 7). The laser parameters and GVD precompensation can be set to optimize the supercontinuum generation in filaments, which leads to a highly collimated white-light beam. This can be used to measure range resolved broadband absorption spectroscopy of trace gases, as has been showed for water vapor in preliminary experiments [22]. Here the narrowness of the water absorption lines was not a difficulty, as it is for the differential absorption lidar (DIAL) technique using two single wavelengths.

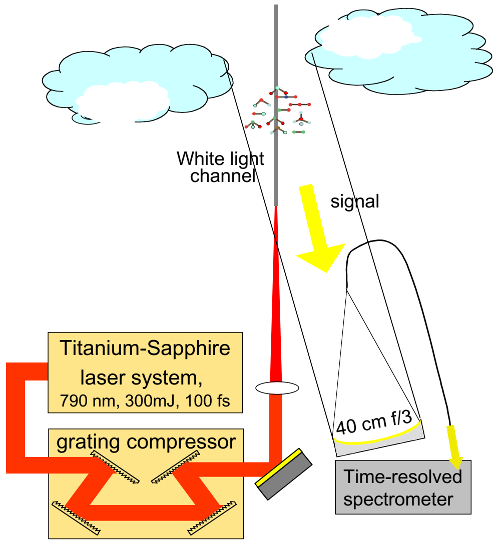

Fig. 7. Setup for white-light lidar experiments.

Besides the use of the white-light supercontinuum, two processes could significantly improve non-linear lidar. On one hand, due to local laser-induced refractive index gradients, the backward supercontinuum emission is significantly enhanced, *i.e.* more supercontinuum is emitted towards the lidar detection system than would be by elastic backscattering [39]. This leads to a significantly improved lidar signal.

On the other hand, theoretical studies [31] and laboratory experiments [40,41] have shown strongly nonlinear interaction of fs-pulses with aerosols, particularly spherical droplets. Processes like Raman scattering [31], multiphoton-excited fluorescence [41] or plasma emission shall lead to a remote analysis of the characteristics, *e.g.* the chemical composition, of atmospheric aerosols.

3.3 Laser-triggered and -guided high voltage discharges

Another application of the Teramobile system was successfully demonstrated in collaboration with the Institute for High Voltage at the Technical University of Berlin. We showed that filaments created by high peak power laser pulses can trigger and guide a discharge between two electrodes. Figure 8 shows the setup used for this experiment.

The mobility of the Teramobile system permitted to install it in the high-voltage hall of the TUB. A high-voltage

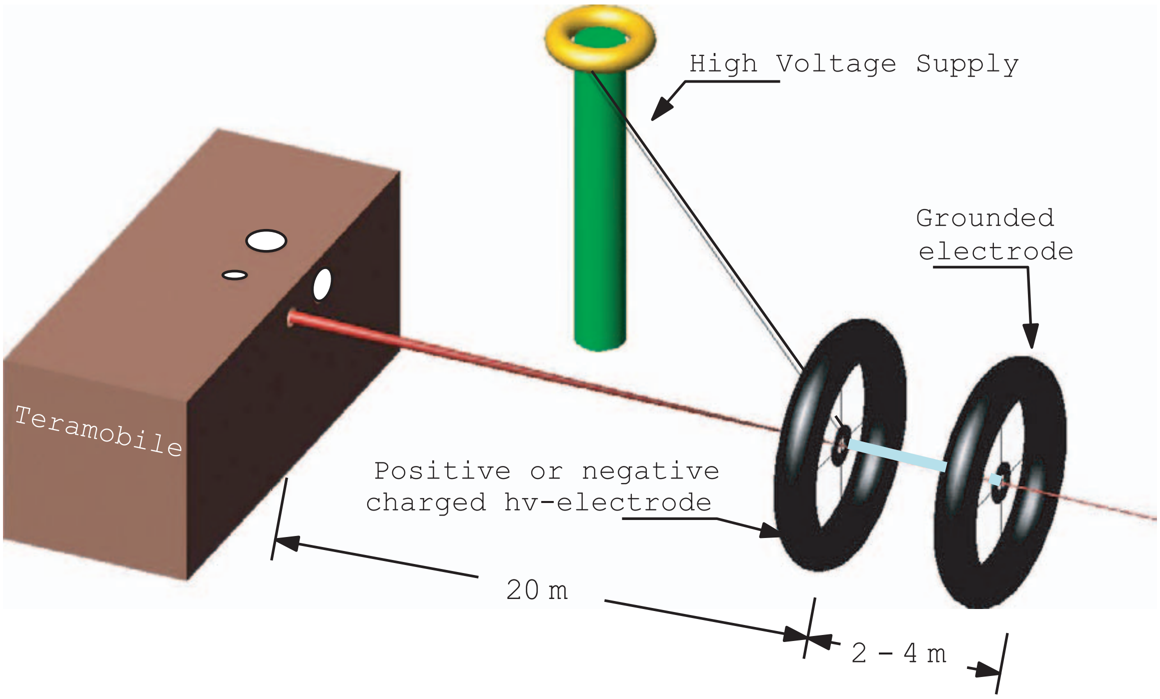

Fig. 8. Experimental setup of the high voltage experiment.

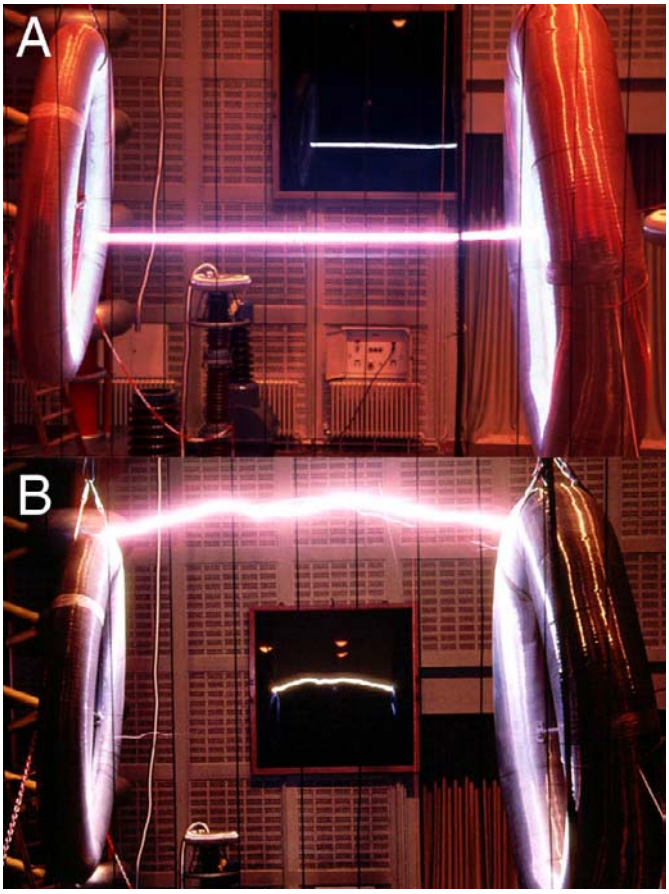

Fig. 9. Discharges with (A) and without (B) laser in a 3.2 m gap between toroidal electrodes. On the laser-triggered discharge (A) the guiding is clearly visible.

(HV) generator (Marx multiplier circuit) provided up to 2 MV pulses (with 1.2 μs rise time) between electrodes separated by a gap, which was adjusted between 1 and 4 m. The laser beam (300 mJ and 100 fs) was aligned to pass successively trough holes in the center of the two electrodes. It was focused slightly before the high-voltage electrode, so that the focus was outside the gap, while the generated filaments spanned over the whole gap. Successful guiding and triggering (*i.e.* occurrence of discharges at voltage that do not permit discharges without laser) of discharges has been achieved for various electrode setups, laser and high voltage parameters.

Figure 9 (A) and (B) respectively show a triggered and guided discharge and a free discharge without laser between two toroidal electrodes of 2.2 m and 3 m diameter. Detailed results of these experiments for different laser and high-voltage parameters will be published elsewhere [42].

4 Conclusion

We successfully integrated a multi-terawatt laser system and a detection unit for lidar, together with their full technical support in a standard 20′ freight container. This system, called Teramobile, has been demonstrated to run as stable as under laboratory conditions. The first obtained results include high-power laser propagation studies, lidar, and high-voltage discharge triggering.

In the near future, the mobility of the Teramobile system will allow us to investigate long distance formation and propagation of self-guided plasma filaments up to several kilometers, as well as lidar measurements optimized for different altitudes and spectral regions or studies of larger distance lightning guiding.

The Teramobile project is funded jointly by the German Deutsche Forschungsgemeinschaft (DFG) and the French Centre National de la Recherche Scientifique (CNRS). J.P. Wolf acknowledges support from the Institut Universitaire de France. We acknowledge a strong support from the technical staffs in the universities of Berlin, Jena and Lyon. We would particularly mention the invaluable help of M. Barbaire, M. Kerleroux, M. Néri, W. Ziegler and M. Kregielski. For the good and fair teamwork in the container planning we like to thank I. Beninga and W. Ruhe from Impres GmbH, J.C. Luderer for his helpful hands and S. Niedermeier for his work in the beginning of the project. Due to the very good collaboration with W. Kalkner's group at the Technical University of Berlin, and particularly Lars Klingbeil and Kay Rethmeier, our first high voltage discharge experiment was a great success. The Teramobile web site is `www.teramobile.org`.

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