PDV INVESTIGATIONS ON THE CESAR FACILITY: 700keV, 350kA PULSED ELECTRON BEAM

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Abstract

Cesar is a high current electron beam facility. It consists of a 2Ω pulsed power generator which can deliver a 350kA, 700kV, 65ns pulsed electron beam thanks to a vacuum diode.

The electron beam is focused on a target material in which it deposits its energy very quickly. Different measurement techniques are investigated such as impulse, rear surface motion or pressure to study thermo mechanical behavior of studied materials and to deduce Equation Of States (EOS). Today, we are focusing on the measurement of surface velocities up to several hundreds meters-per-second on different types of shock physics experiments. It is a time resolved surface velocimetry using the heterodyne technique. This diagnostic is assembled with commercially available 1550nm single-mode fiber lasers to deliver light to and from the target. The return Doppler-shifted light is mixed with the original laser light to generate a beat frequency proportional to the velocity.

We describe here, the generation of this high intensity electron beam and our approach to measure velocities with heterodyne technique. We present recent data obtained with this diagnostic.

INTRODUCTION

Potassium dihydrogen phosphate (KH_2PO_4 or KDP) crystals are used for the frequency conversion in high power lasers such as NIF in the USA and LMJ in France being developed for inertial confinement fusion. It has been shown that efficiency of laser lines is limited mainly by laser-induced damages (LID).

LID in KDP by nanosecond pulses involves various material phases, from solid state to plasma leading to the creation of a shock wave whose pressure lies in the GPa range. In order to enhance the resistance to laser damage of these crystals, it is necessary today to determine the mechanical response of KDP crystals under thermodynamic conditions within the pressure range under considerations [1].

CESAR is a high current electron beam facility of the French Alternative Energy and Atomic Energy Commission (CEA), CESTA center. It consists of a 2Ω pulsed power generator which can deliver a 350kA, 700kV, 65ns FWHM pulsed electron beam. By focusing this electron beam on a target, we convert electrical energy into thermal and mechanical energy leading to shock wave and surface velocities from few m/s until hundreds m/s.

Velocities as a function of time is then the main diagnostic required for these types of shock physics experiments. It is also a useful way to analyze the beam, and especially its fluence and its spatial energy distribution.

We describe here, a whole experimentation in which a high energy electron beam is implemented to create a shock wave in a KDP crystal. Velocity measurement of the rear surface of this crystal is realised using the Photon Doppler Velocimetry (PDV) method.

THE CESAR FACILITY

The CESAR generator was designed and built in 1988. In order to deliver a high energy electron beam, it associates a Marx generator and four successive coaxial water lines to drive a 2Ω diode [2].

The high pulsed power generation

The Marx generator is composed of twenty 0.347µF capacitors which correspond to a stocked energy of 120kJ at a nominal charging voltage of 120kV.

It delivers a 2.4MV bi-exponential pulse to a 3.35Ω storage line. A self-breakdown water switch transfers energy from this line to the 2Ω/30ns pulsed forming line that shapes the square waveform of the voltage signal [3].

Then the pulse is delivered to the diode via two 2Ω transmission lines separated by a 8 pressurized canals switch which stop the electrical prepulse.

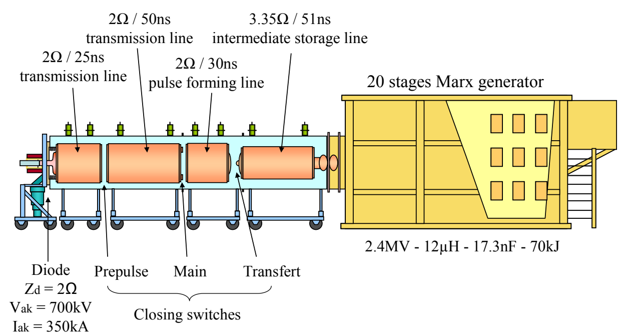

Figure 1: Schematic view of CESAR.

The vacuum diode and the beam transport tube

The vacuum diode (10^{-5}mbar) is the final element of the electrical circuit, fixed on the inner and outer conductors of the last coaxial transmission line. It controls the overall impedance. Its coaxial structure contributes to reducing its self inductance (30nH). It is made of a radial insulator, an electric field divider, a stainless cathode and a 6µm aluminized Mylar anode.

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The 700kV electrical pulse is applied to the cathode, whereas the anode is connected to the ground potential. High electric field (>10^5V/cm) create a plasma at the cathode surface from which electrons are extracted.

The electron beam is then guided to a target located after the anode, at the focus point of two coils which generate a pulsed longitudinal magnetic field (B_Z).

To eliminate the space charge effect, the cavity downstream the anode is filled with 1mbar of air in which the beam generate a plasma (Fig. 2).

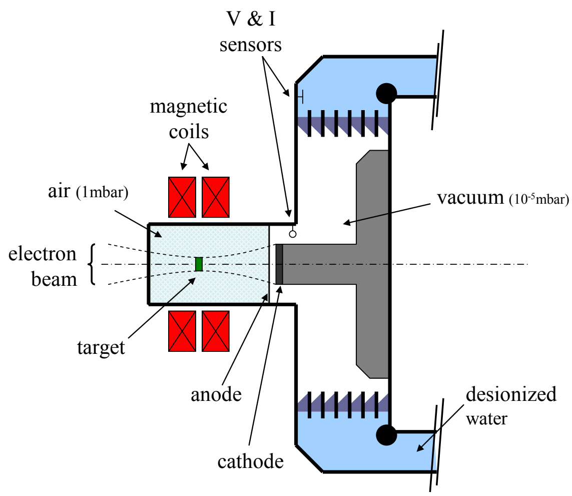

Figure 2: Geometry of the diode.

By moving the distance between the focusing point and the cathode and by using different cathode diameters, we can adjust the energy density applied on the target from 10cal/cm² (40J/cm²) to 500cal/cm² (2kJ/cm²).

Voltage and current on the diode are respectively measured by capacitive dividers or D-dot and B-dot sensors.

VELOCIMETRY MEASUREMENT USING PDV METHOD

Traditionally, there have been two methods used for measuring velocities in the km/s range: Fabry-Pérot and VISAR (Velocity Interferometer System for Any Reflector). The PDV method, as these two techniques, measures velocity continuously as a function of time.

Photonic Doppler Velocimetry (PDV)

The moving surface to be measured is illuminated by a laser at frequency f_0 (Figure 3). Optical fibers are used to transport light from the laser to a probe containing a focusing lens. This same probe then collects a fraction of the light that is scattered or reflected from the moving surface and sends the Doppler-shifted light f_d to the detector. For the heterodyne method, a similar amount of non-Doppler-shifted light f_1 is sent directly from a reference laser to the detector (generally, only one laser is used, by some means, a fraction of the f_0 light is transported directly to the detector without being Doppler-shifted).

It interferes with the Doppler-shifted one and generates a beat signal with frequency f_b given by:

$$f_b = f_d - f_1 = 2\frac{v}{c} f_1$$

With the speed of light $c = \lambda_1 f_1$, where λ_1 is the wavelength emitted by the laser. The velocity is:

$$v = \frac{\lambda_1}{2} f_b$$

With a laser wavelength of 1550nm, the velocity is simply,

$$v(m/s) = 775 f_b \,[GHz]$$

In almost of our shock physics applications, the surface is moving toward the probe so that $f_d > f_0$.

System design

The entire system is fiber coupled, except from the probes to the surface. For three main reasons (easier adjustments before the shot, velocity range doubling and ability to directly measure negative velocities), a second laser with a shifted frequency f_1 (a few GHz compared to f_0) is used [5]. Figure 3 shows the detailed diagram of our 4-channel setup. The first laser is a 1550nm single mode *Keopsis* laser, 2W, 400mW/channel. The second one is also a single mode 1550nm *Keopsis* laser but with adjustable frequency-shift (several GHz) and only 50mW, 10mW per channel.

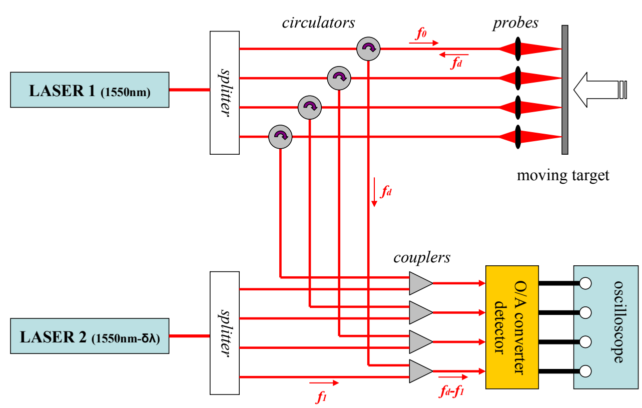

Figure 3: Schematic diagram of the 4-channels PDV set.

Light is transported by means of single mode fiber SMF28e until *OZ optics* or *Lightpath compagnies* probes. Detector is a NewFocus with a 12GHz bandwidth and a sensitivity of 750V/mW. Signals are recorded using a *Lecroy* 8500A digitizer (bandwidth = 5GHz, sampling = 10Gs/s, 4 channels).

APPLICATION ON SHOCKED OPTICAL COMPONENT (KDP)

Experimentation set

This is the 3038th shot on the CESAR facility. The average fluence of the shot is deduced from the beam

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total energy (via diode current and voltage signals) and area of the quasi circular shape the electron leaves on the sample graphite holder. Focus point of the coils and anode-KDP sample distance are set such as the fluence is closed to 40cal/cm² on the target. Beam diameter at the target place is approximately 10cm.

The experimental setup is shown in Figure 4. It consists of a 3mm thick, 50mm diameter, aluminium buffer in which the energy of the electron beam is converted into thermal and mechanical energy, allowing a dynamic shock wave to propagate through the 5mm thick, 50mm square plate, KDP sample, to which it is bonded with an epoxy resin (glue layer thickness less than 10µm). The rear face of the KDP sample is bonded to a LiF window (15mm radius and thickness) characterized by a thin vapour-deposited metallization at their interface. It behaves as a perfect mirror on which lasers of the PDV systems can be reflected.

The first velocity record (PDV1) is on the main axis and the three others (PDV2, PDV3, PDV4) are 100mm off-axis 120° from one another. The graphite diaphragm ahead of this whole assembly that maintains it on a metallic stand stops the outer part of the beam.

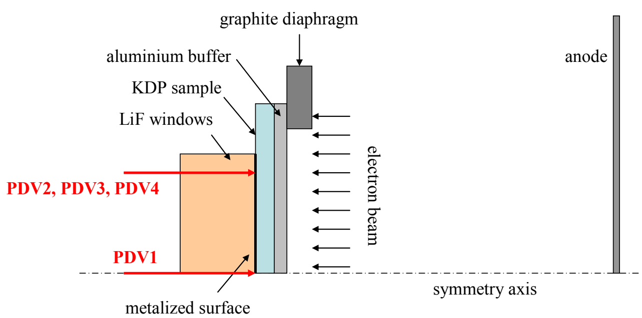

Figure 4: Experimental setup for the KDP crystal test.

Photography on Figure 5 illustrates the target assembly under test (without the graphite diaphragm).

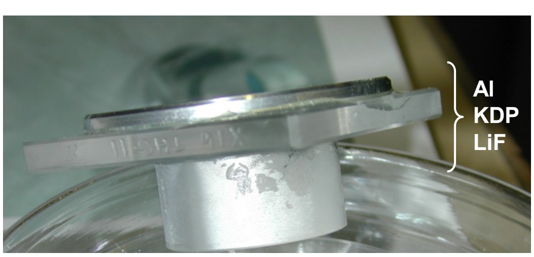

Figure 5. Al/KDP/LiF experimental stack.

Diode electrical signals

Figures 6 and 7 show the electrical voltage and current signals measured on the cathode. Peak voltage and current are respectively 730kV and 370kA.

Energy transfer is optimum when the diode impedance is equal to the output line impedance of the generator, 2Ω.

The diode impedance is varying with time as plasma moves in the anode-cathode gap:

$$Z_{diode}(t) = \frac{k(V)}{\sqrt{V}} \frac{d - vt}{r_c^2}$$

where, k is 136 for relativistic electrons, d the anode-cathode gap, v the moving speed of plasmas in the gap, t the time, V the generator output voltage and r_c the cathode radius.

Diode impedance is 2Ω for the peak power maximum. Energy coupled to the electron beam is higher than 14kJ.

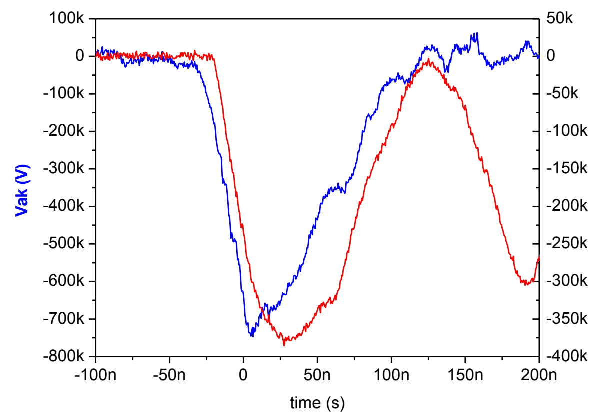

Figure 6: Voltage (Vak) and current (Iak) waveforms on the diode.

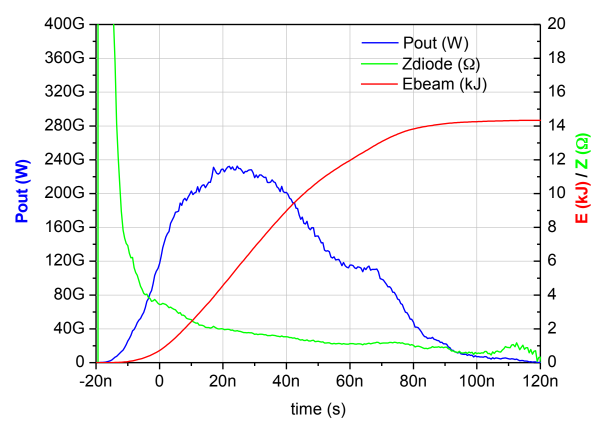

Figure 7: Energy coupling to the electron beam.

Results of shock arrival measurements

Some preliminary shots on aluminium target (i.e. without KDP) have been made to validate the reproducibility of the generated stress wave. It is seems to be better than 5%. These shots also allow an estimation of the spatial uniformity of the beam energy density distribution by means of velocity measurements on the target. It has been observed that on-axis peak velocities are weaker than the off-axis ones. Relative difference is less than 23% in the worst case.

Low fluence experimental results are presented on Figures 8 and 9. The first one is the spectrogram of PDV1, resulting from an instantaneous short time Fourier transform that is performed within a time window (a few ns width, rectangular or Gaussian shape) shorter than the signal under consideration. The Fourier transform displays all the frequencies and therefore all the velocities with their relative intensity. Lasers used in this PDV system are not strictly single-mode and have harmonics that's why the spectrogram shows two time-velocities diagrams.

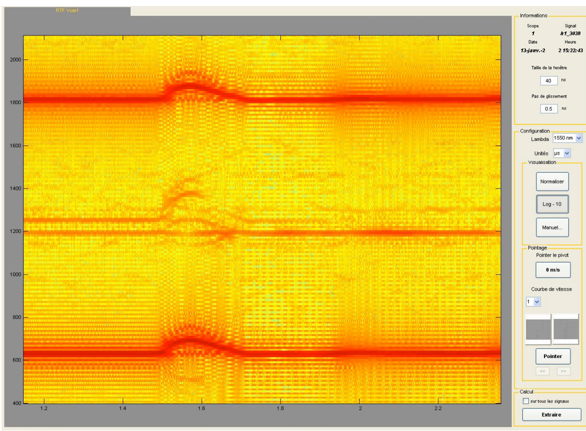

Figure 8: PDV1 spectrogram.

PDV1 velocity as a function of time is then extracted from the spectrogram. The same operations are done for the three others channels and plotted in Figure 9.

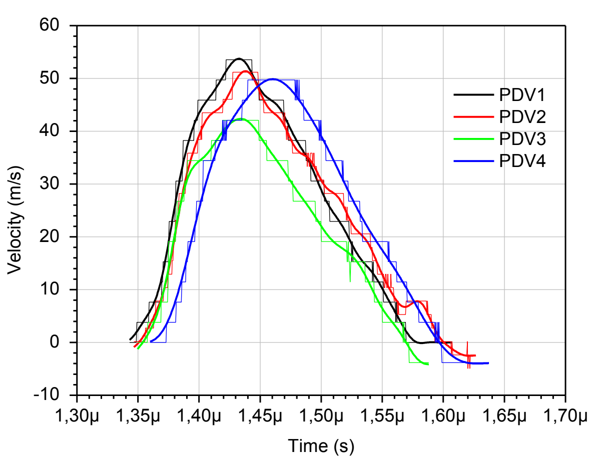

Figure 9: Velocity as a function of time for each of the 4 PDV channels.

Peak velocities recorded are approximately 53.7m/s for PDV1, 51.4m/s for PDV2, 42.4m/s for PDV3 and 50m/s for PDV4. A visual control of the front face of the aluminium buffer (under electron beam flux) does not permit to conclude about this slight peak velocity dispersion. Interpretation of these results needs some comparisons with physical simulations.

SUMMARY

We have used the heterodyne technique to design and assemble a PDV system using commercially available components.

Some experimental data have been obtained for KDP crystal under dynamic stress. This experimental investigation combines the generation of a high energy electron beam with the CESAR facility, its focusing on a target stack and PDV measurements of rear surface velocity. These experimental data can be compared to simulation models in order to deduce equation of state of the KDP crystal to understand laser-induced damage in the nanosecond regime.

Moreover, PDV measurements give some important results to characterize the electron beam, especially its fluence and its energy spatial distribution.

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