Scientific and Technological Issues on the Application of High Intensity Lasers to Material Properties Modification: The case of Laser Shock Processing of Metallic Alloys

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Scientific and Technological Issues on the Application of High Intensity Lasers to Material Properties Modification: Laser Shock Processing of Metallic Alloys

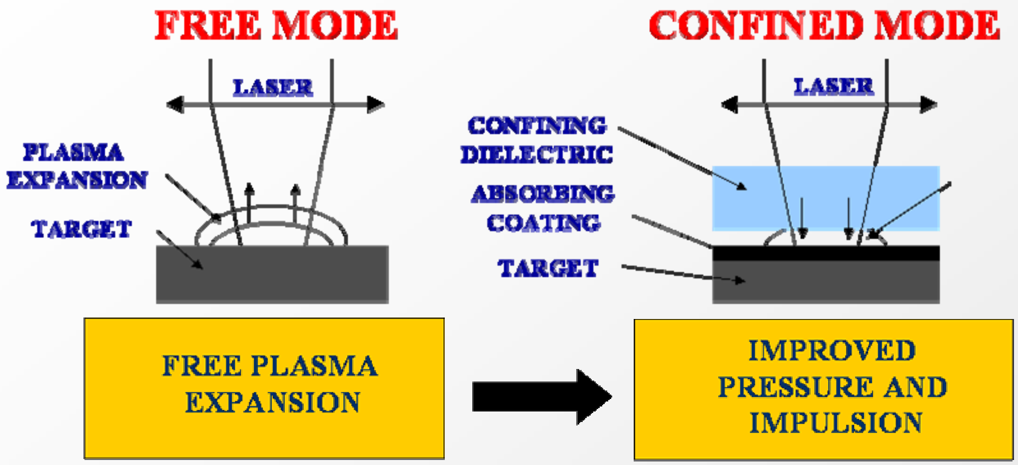
OUTLINE:

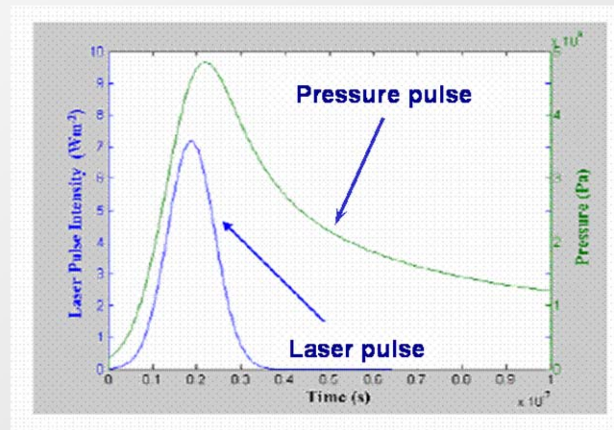
- Introduction
- Physical Principles of LSP
- Numerical Simulation. Model Description
- Simulation Results
- Experimental Validation. Diagnosis Setup
- Discussion and Outlook

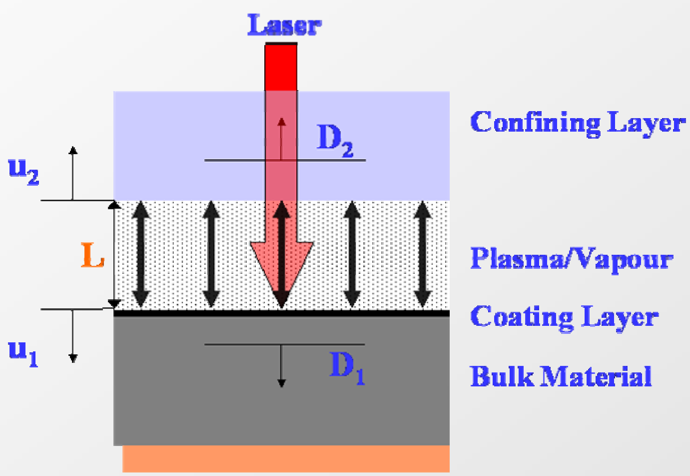
1. INTRODUCTION

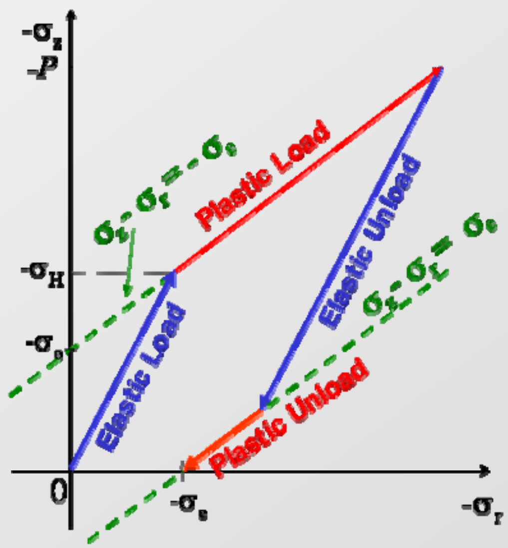
- **Laser Shock Processing (LSP) has been practically demonstrated as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection. Experimental results obtained with commercial Q-switched lasers prove complete feasibility at laboratory scale**
- **Depending on initial material mechanical properties, the remaining residual stresses fields can reach depths and maximum values providing an effectively enhanced behaviour of materials against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions. This makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.**
- **However, according to the inherent difficulty for prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability**
- **A physically comprehensive calculational tool (SHOCKLAS) has been developed able to sistematically study LSP processes**

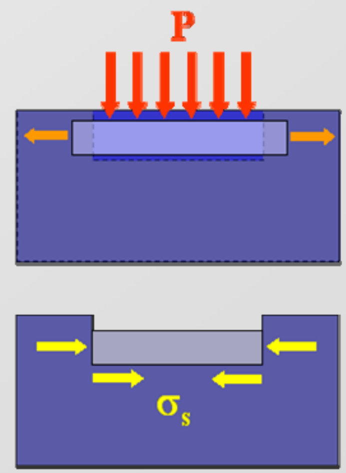
2. LSP PHYSICAL PRINCIPLES (1/2)



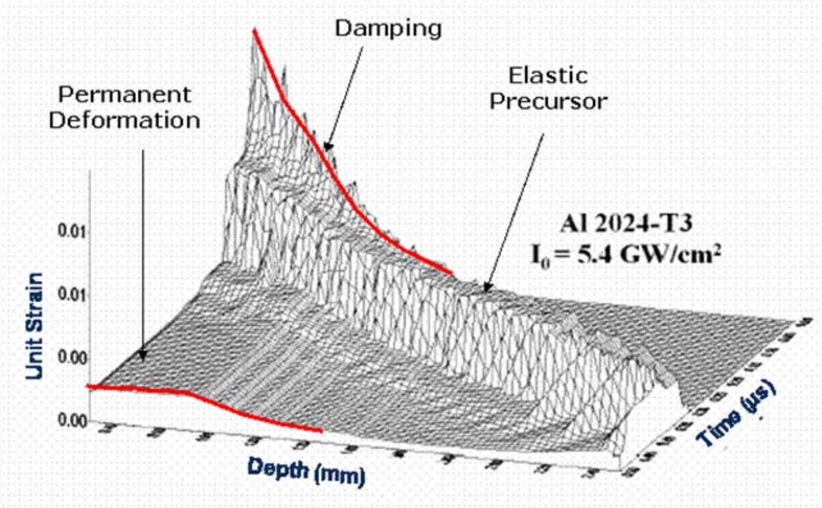


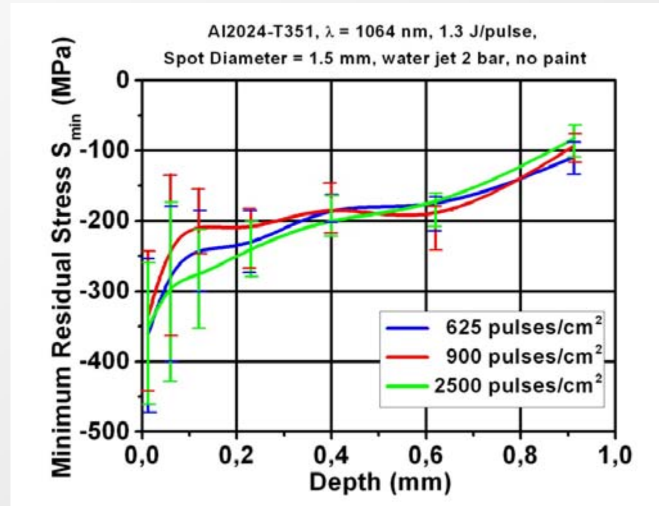


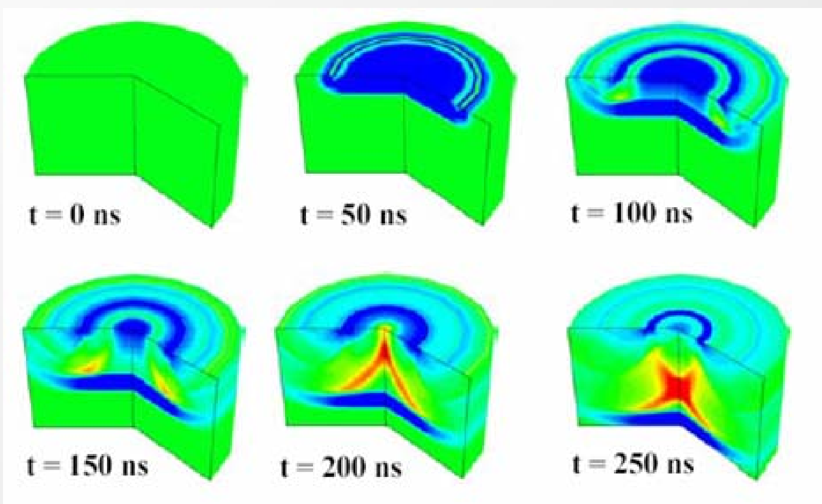


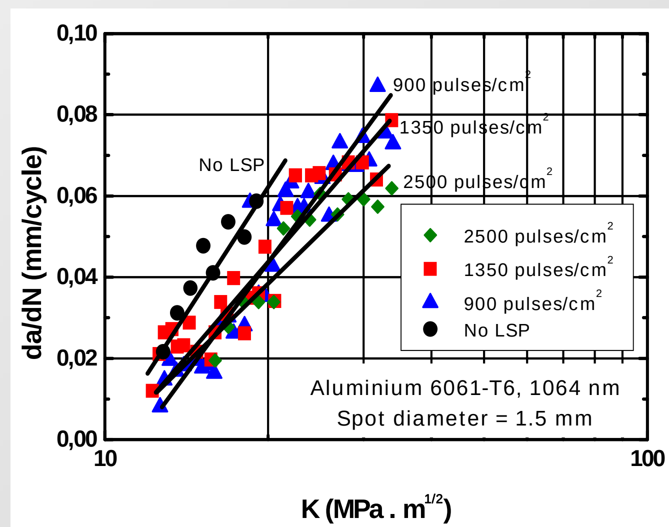


2. LSP PHYSICAL PRINCIPLES (2/2)

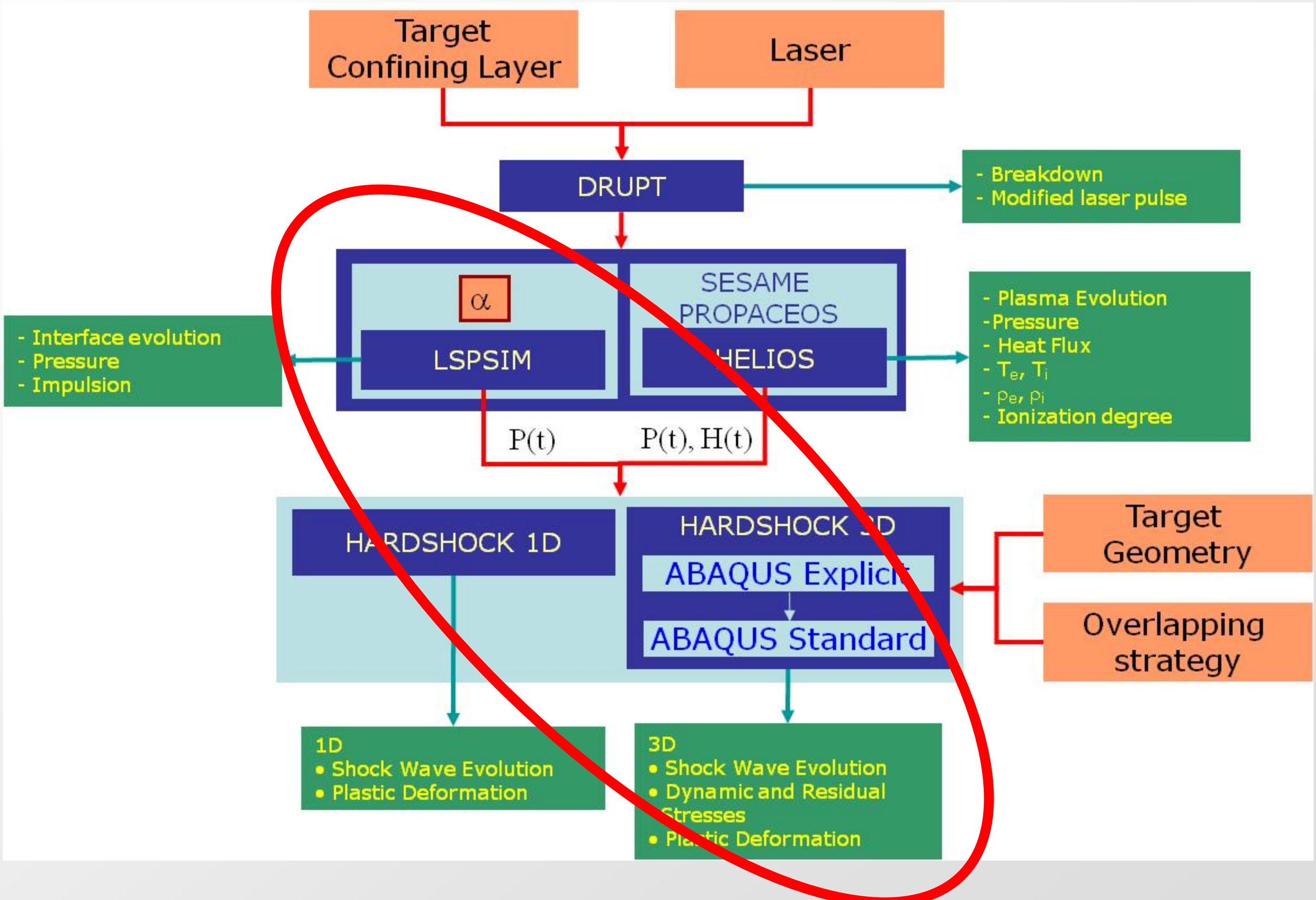




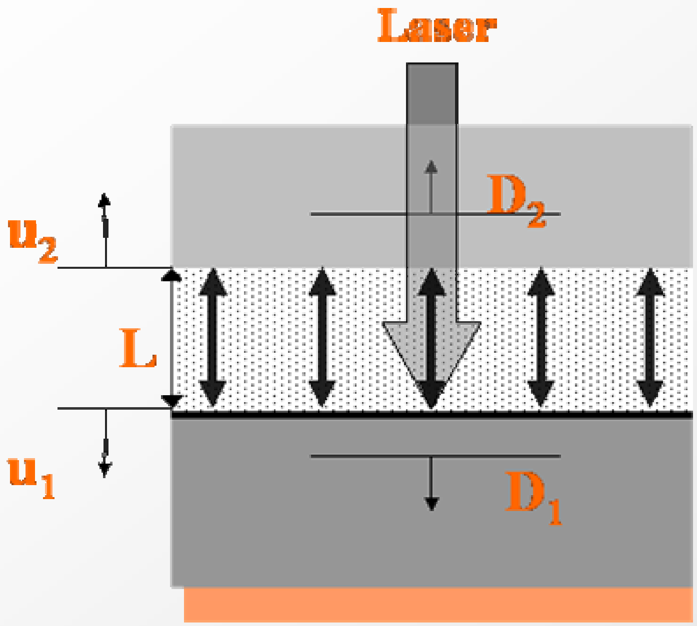




The SHOCKLAS Calculational System



3. NUMERICAL SIMULATION. MODEL DESCRIPTION



LSPSIM

Interface thickness

$$L(t)=\int_0^t \left[u_1(t)+u_2(t)\right]dt$$

Shock wave relation

$$P=\rho_i D_i u_i$$

Heating phase

$$I(t)=P(t)\frac{dL(t)}{dt}+\frac{d\left[E_i(t)L(t)\right]}{dt}$$

$$P(t)=\frac{2}{3}E_i(t)=\frac{2}{3}\alpha E_i(t)$$

Solid/Liquid $D=C+Su$

Gas $D=u=\left(\frac{(\gamma+1)}{2}\frac{P}{\rho}\right)^{1/2}$

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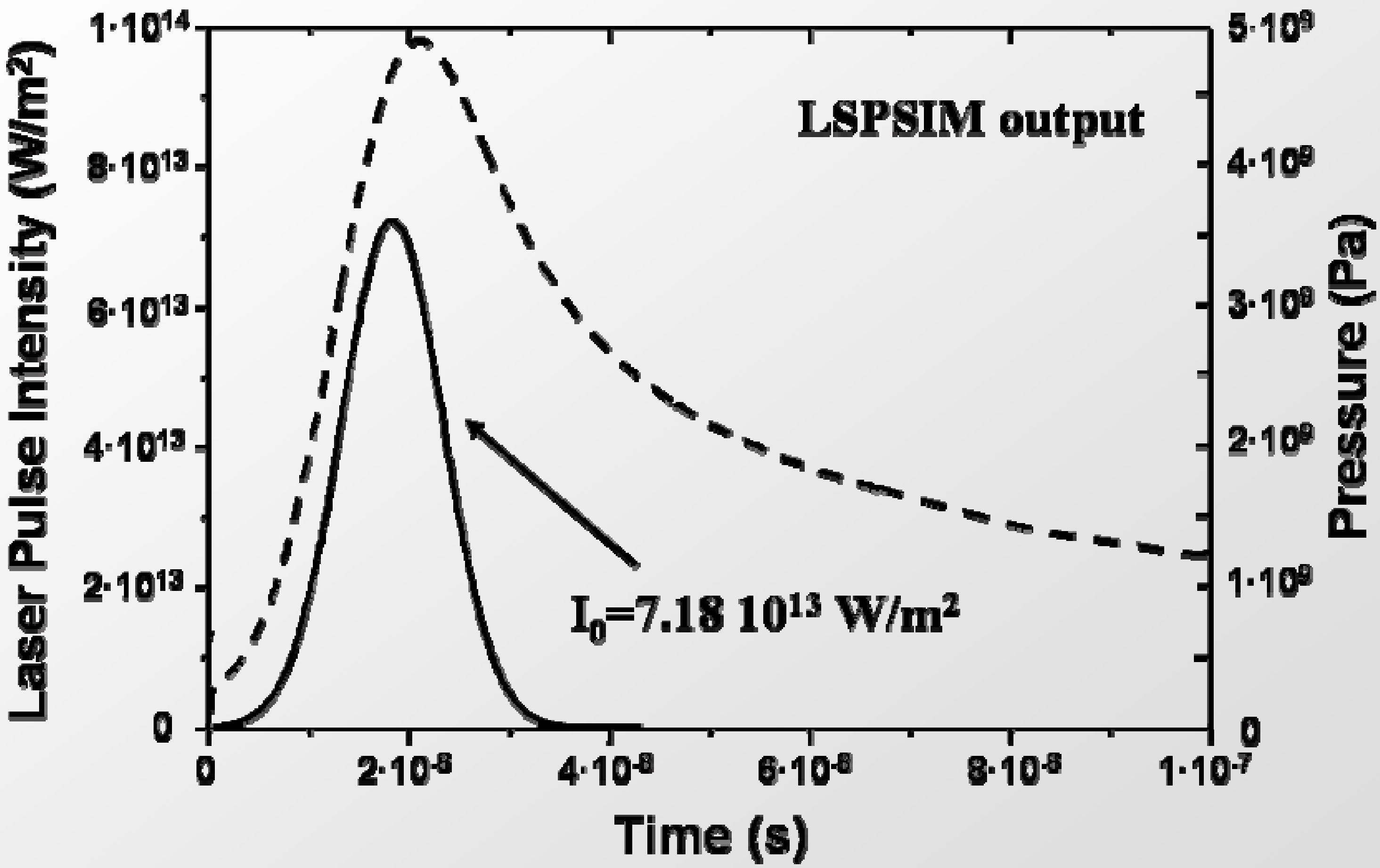

3. NUMERICAL SIMULATION. MODEL DESCRIPTION

HARDSHOCK

- 1D Motion: Mass
  Momentum
  Energy

  (Method of characteristics)

$$\rho_1 u_1 = \rho_0 u_0$$
$$P_1 + \rho_1 u_1^2 = P_0 + \rho_0 u_0^2$$
$$\varepsilon_1 + \frac{P_1}{\rho_1} + \frac{u_1^2}{2} = \varepsilon_0 + \frac{P_0}{\rho_0} + \frac{u_0^2}{2}$$

- Hydrodynamic/elastic-plastic
  (Von Mises yield criterion)

$$|\sigma_x - \sigma_r| < -YS$$

- Ideal gas/Grüneisen E.O.S.

$$P = P_h + \Gamma\rho(W - W_h)$$
$$W_h = \frac{P_h\varepsilon}{2\rho_0} \quad P_h = \frac{\rho_0 C_0^2 \varepsilon}{(1 - S\varepsilon)^2}$$
$$U_s = C_0 + S \cdot U_p$$

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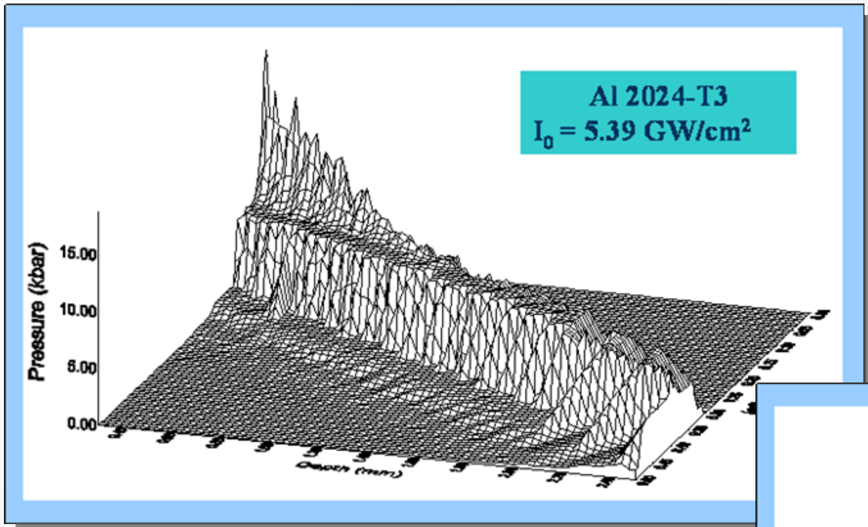
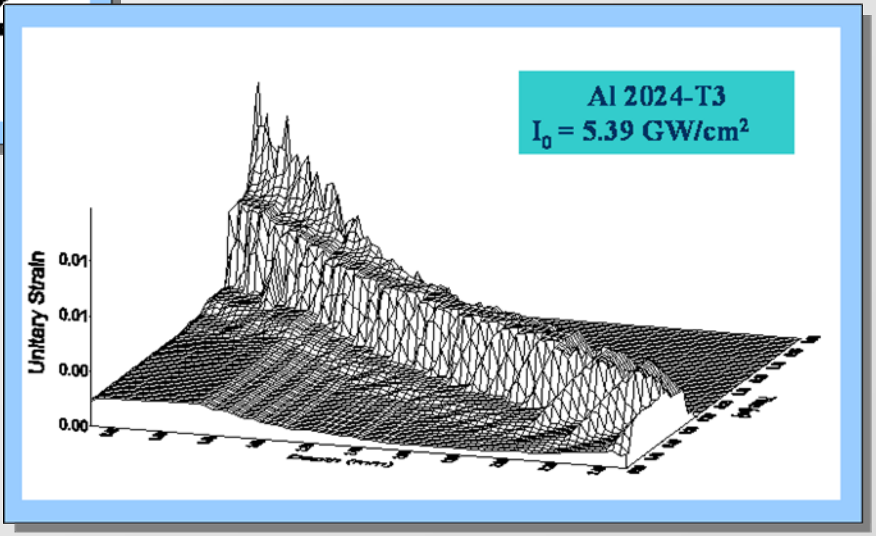
HARDSHOCK



HARDSHOCK

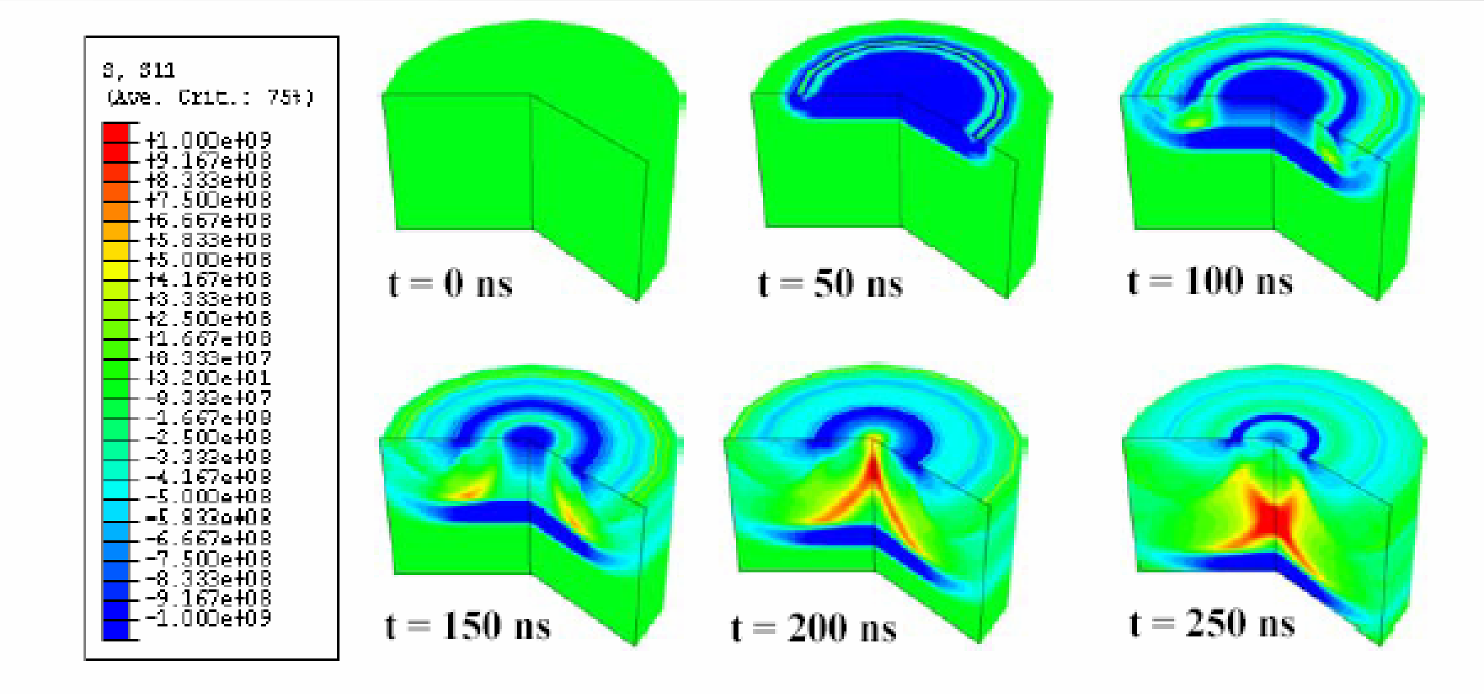


3. NUMERICAL SIMULATION. MODEL DESCRIPTION

HARDSHOCK-2D Semi-infinite

Ti6Al4V

Radial stress dynamic analysis



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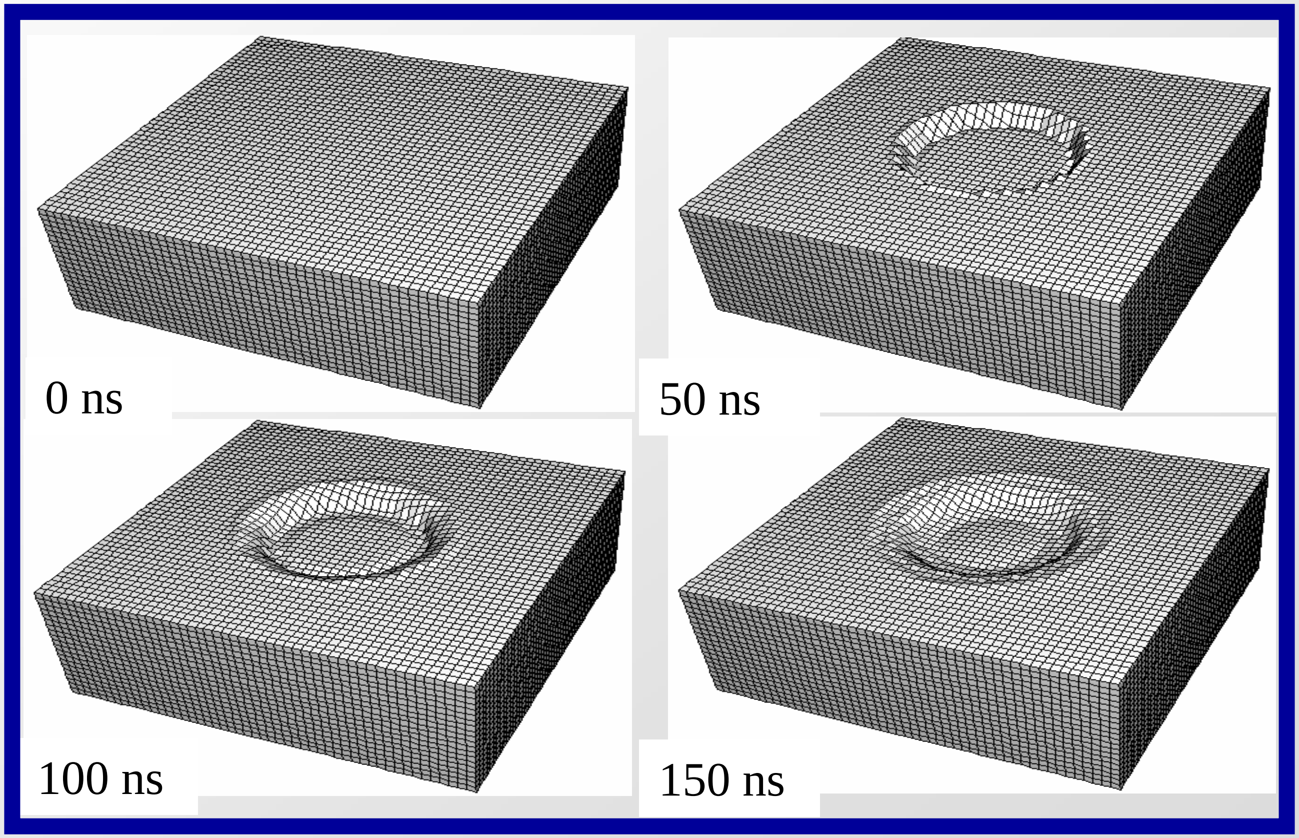
HARDSHOCK-2D Semi-infinite

Ti6Al4V

Nd:YAG (1064 nm)
P_{av}= 5,7 W/cm^2
Spot radius = 0.75 mm
FWHM = 0 ns
α = 0.15

Multiple shocks dynamic analysis



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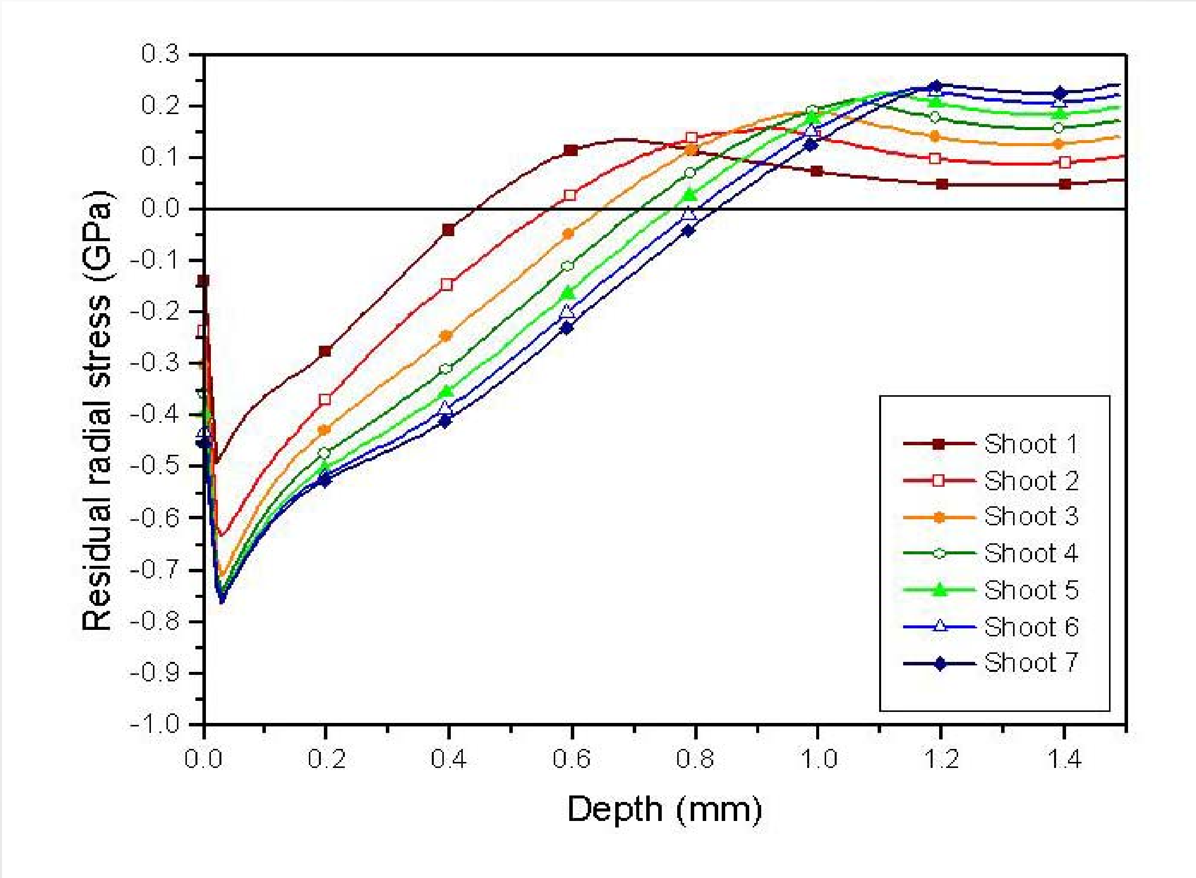

Multiple shocks dynamic analysis

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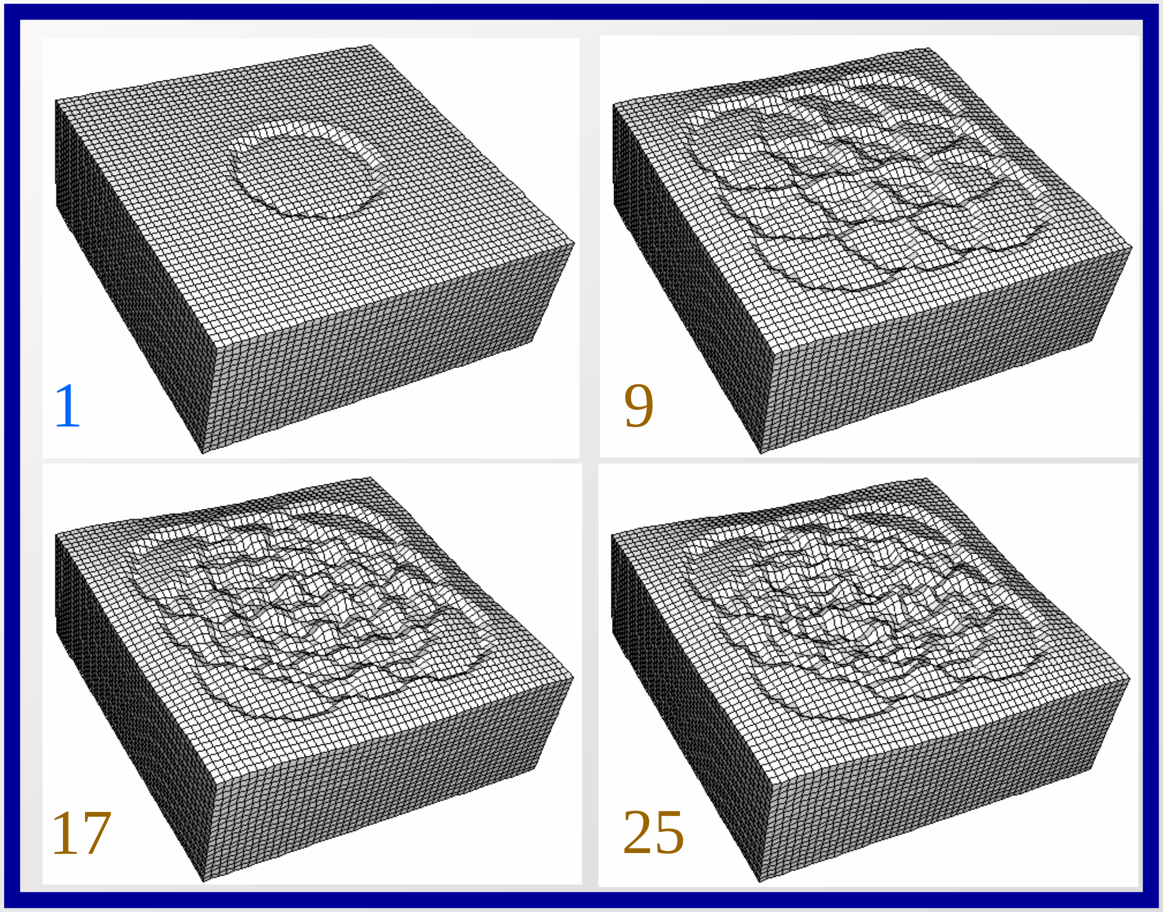
HARDSHOCK-3D (full scope)

Ti6Al4V

Nd:YAG (1064 nm)
P_{av}= 5,7 W/cm^2
Spot radius = 0.75 mm
FWHM = 0 ns
α= 0.15
Overlapping = 900/cm^2



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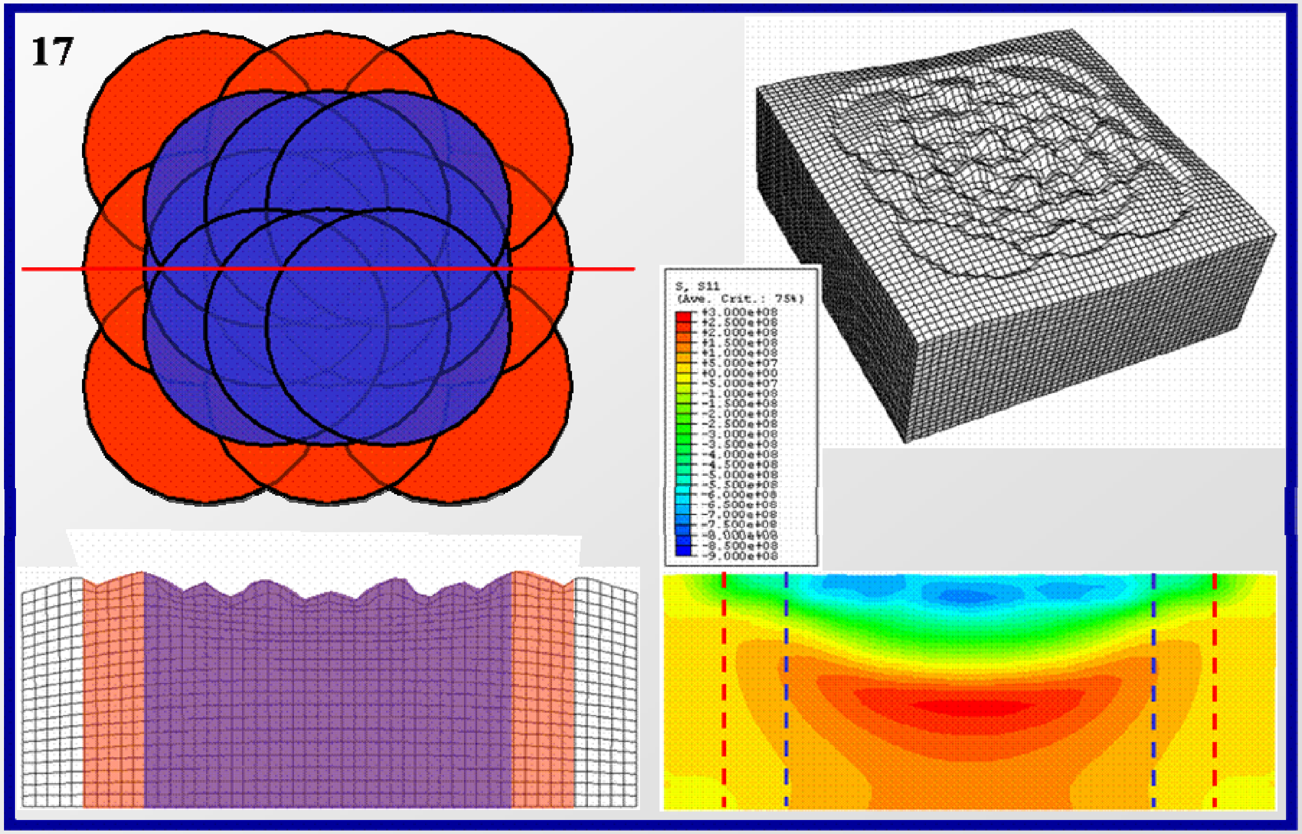
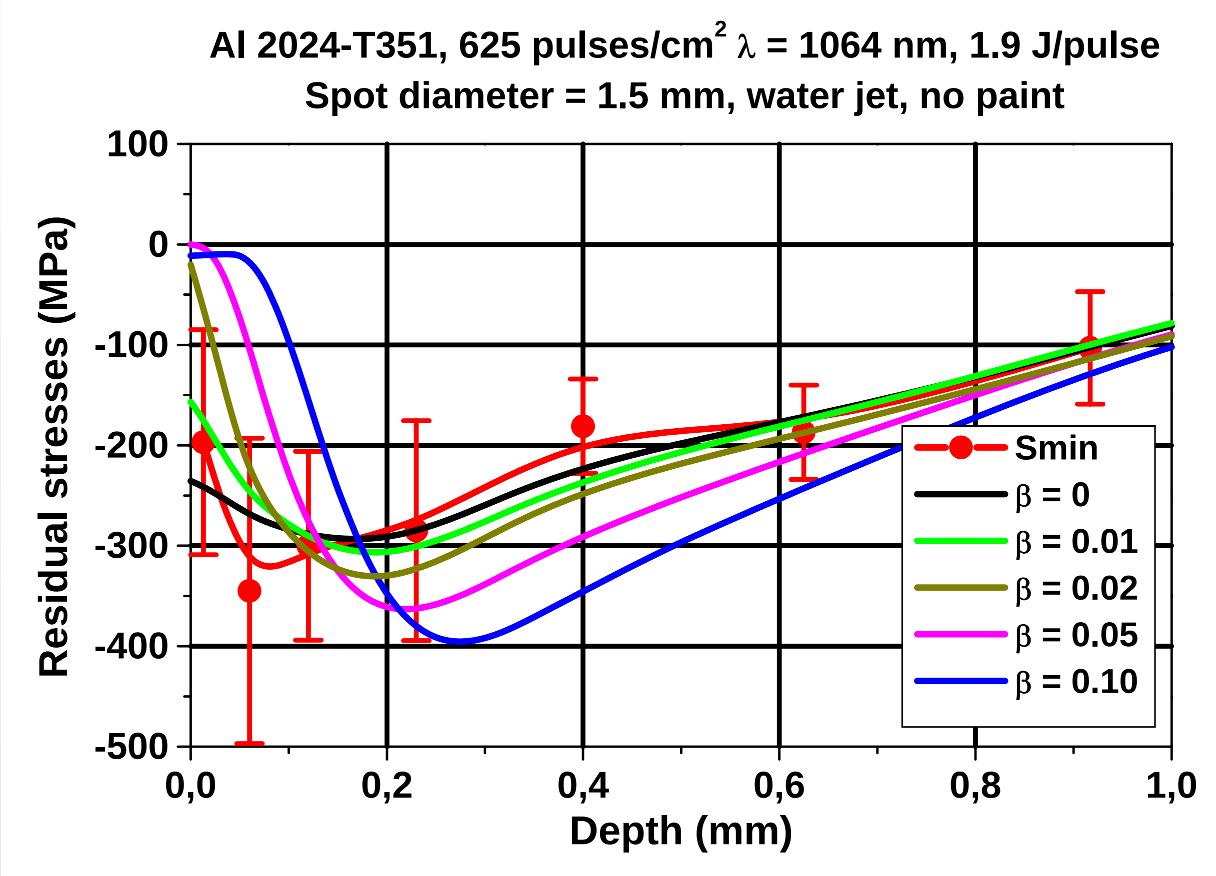


3. NUMERICAL SIMULATION. MODEL DESCRIPTION

Analysis of relative influence of thermal and mechanical effects

Al2024-T351



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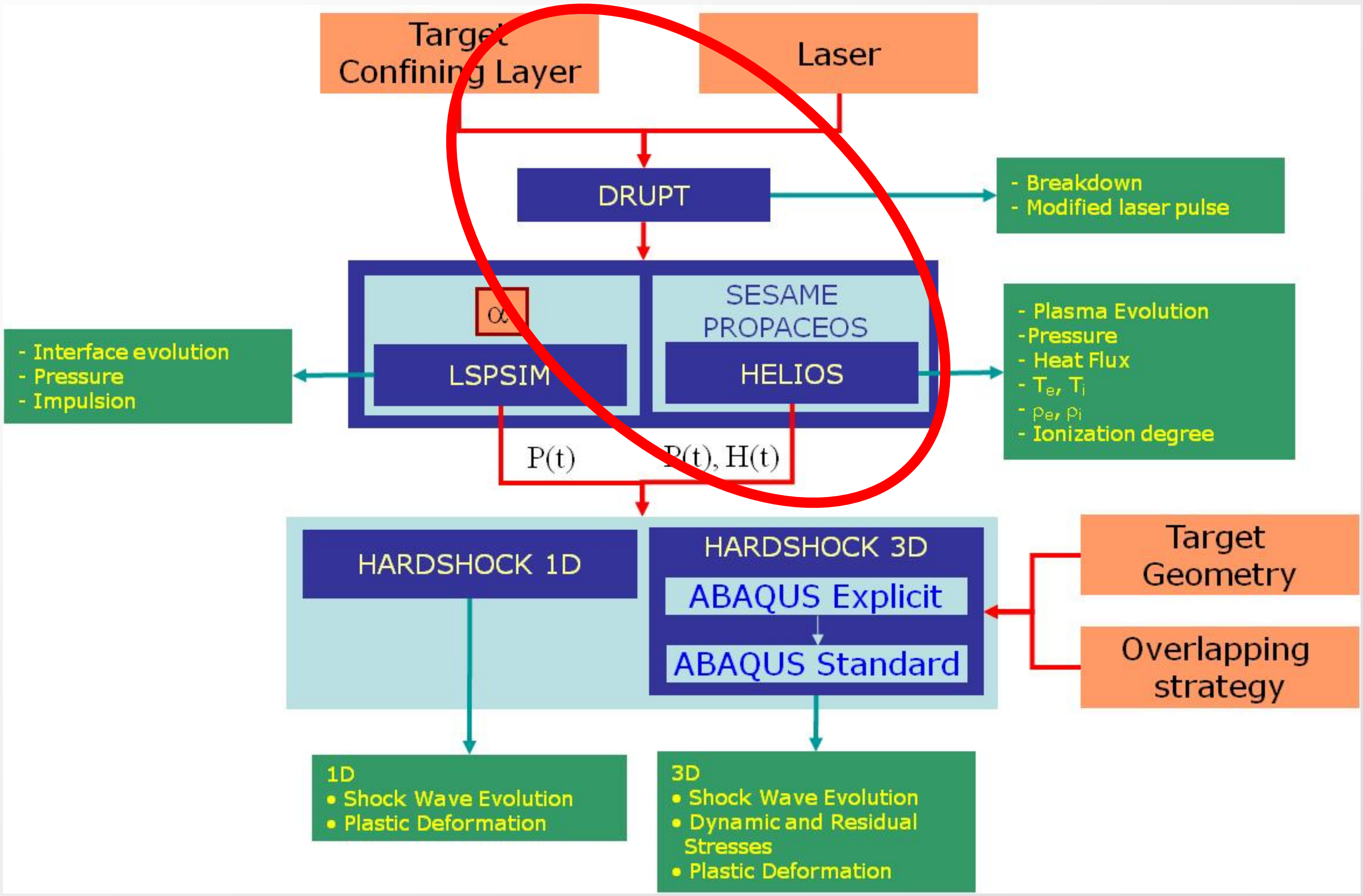

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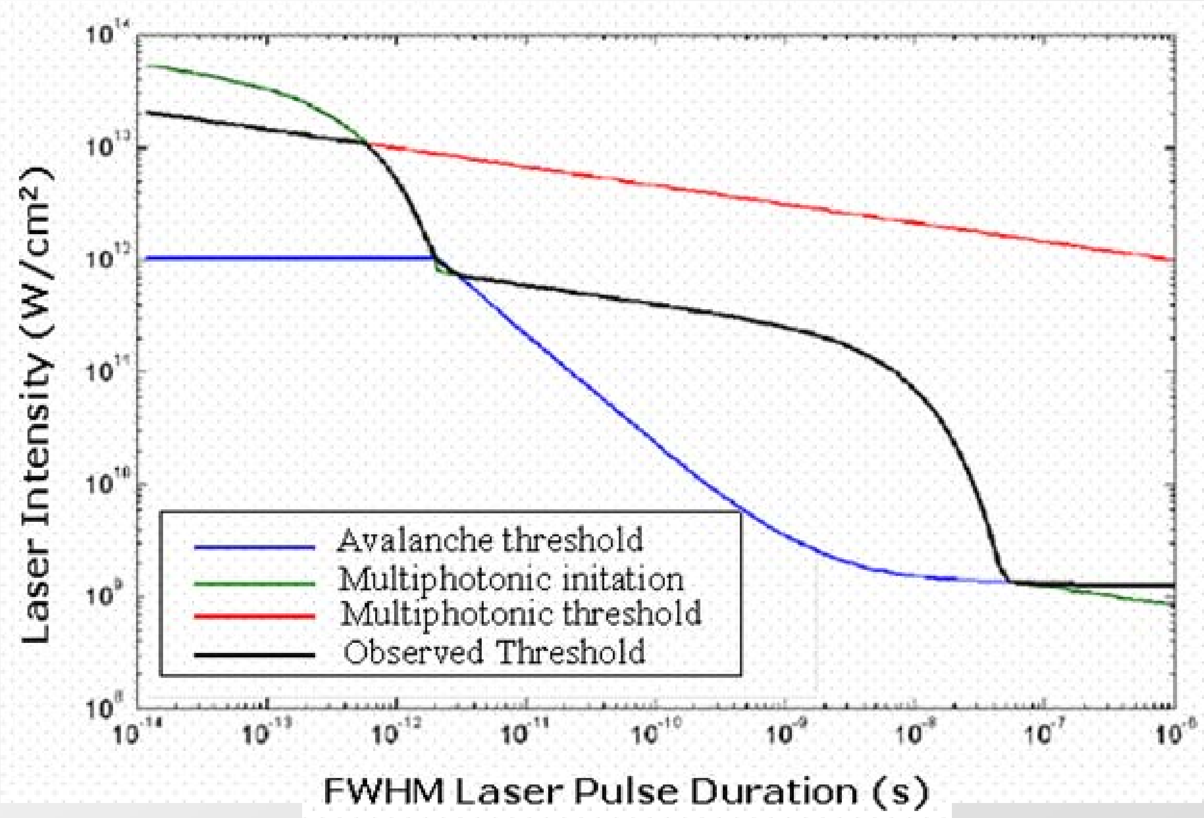
DRUPT



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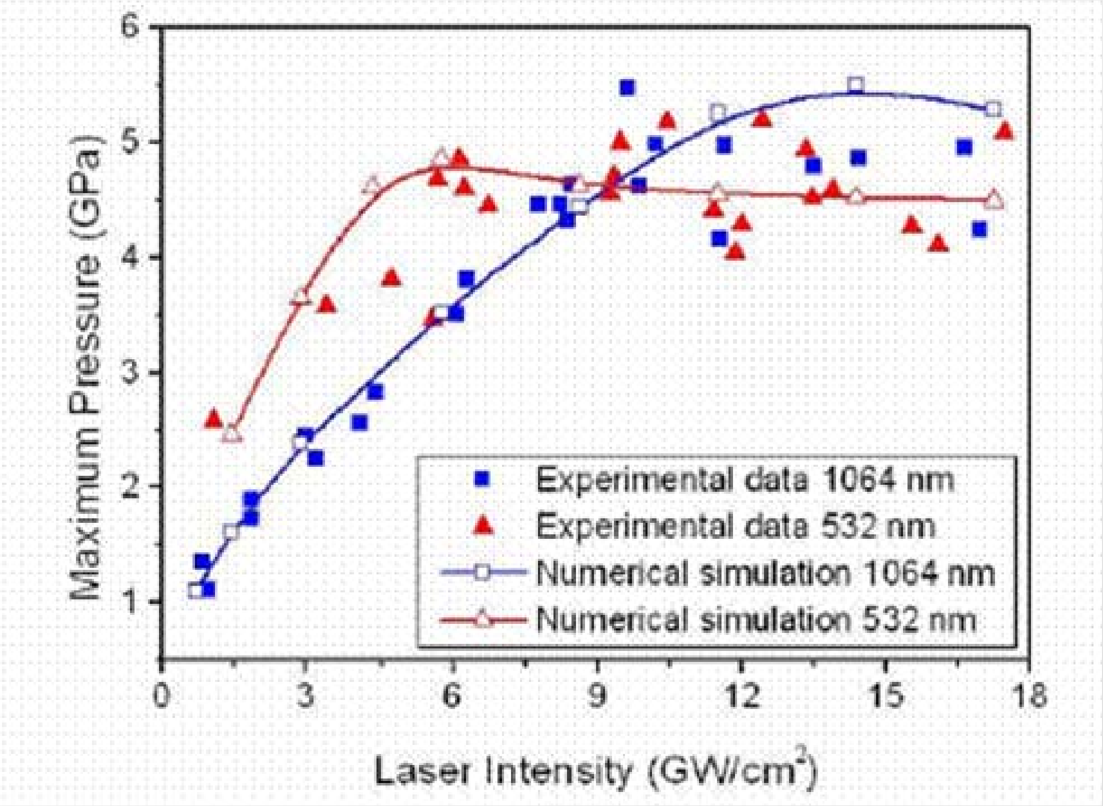
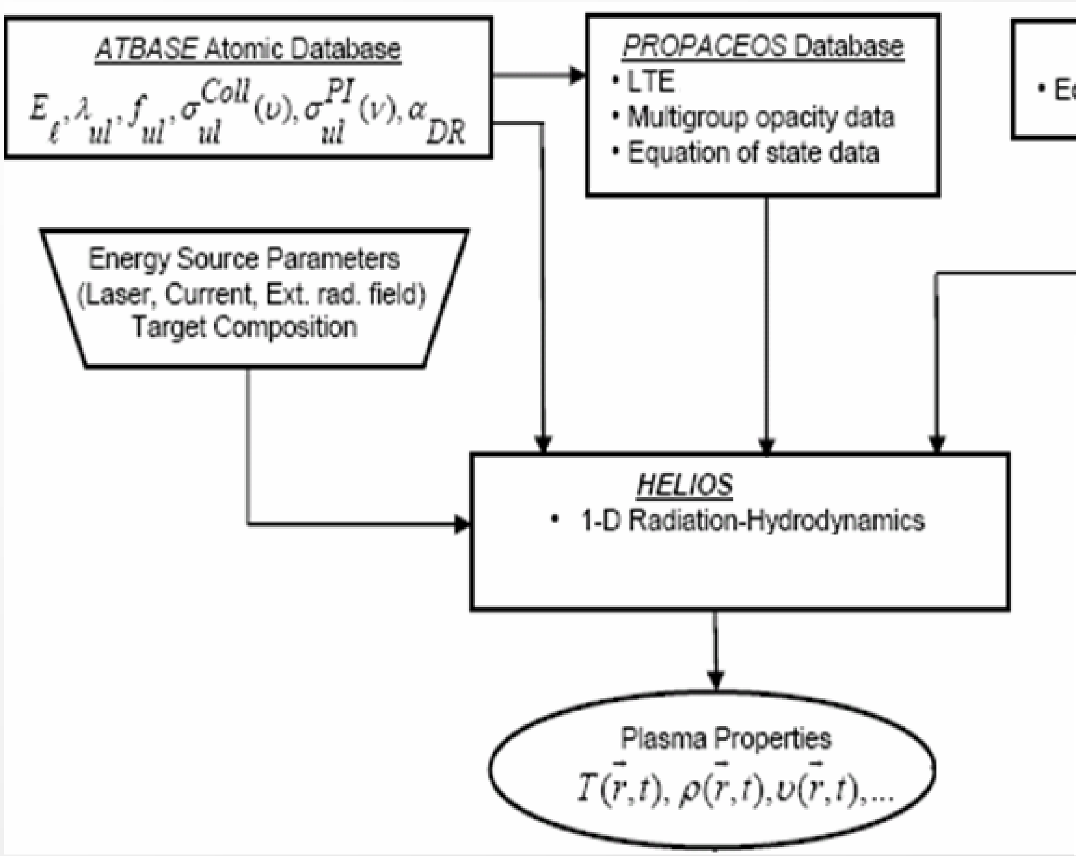
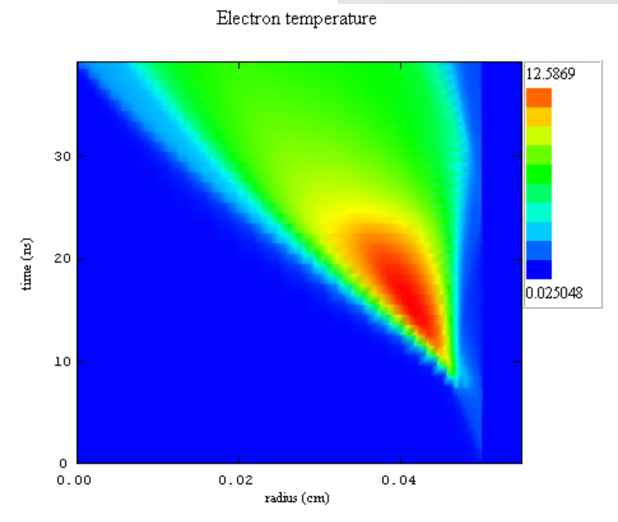


3. NUMERICAL SIMULATION. MODEL DESCRIPTION

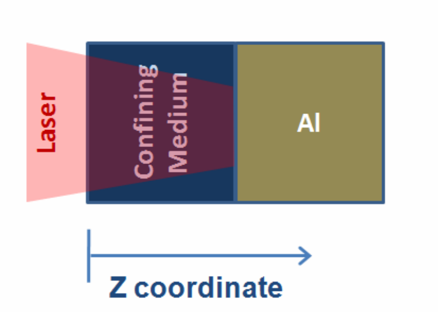
HELIOS

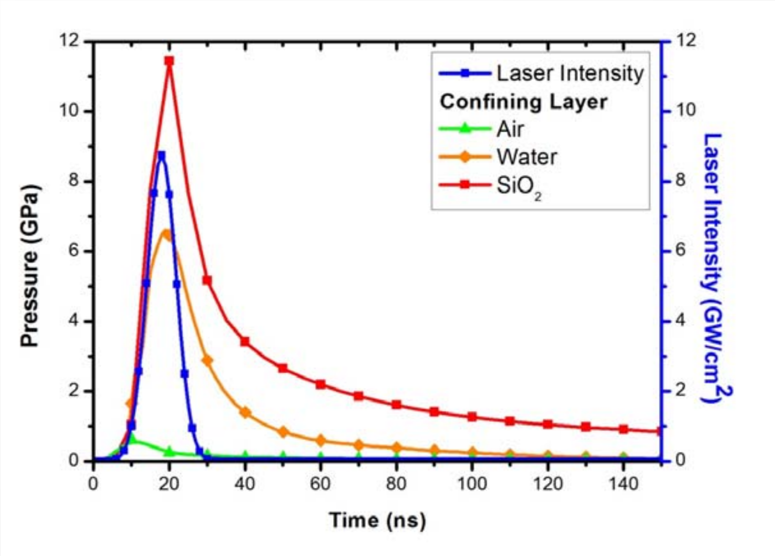


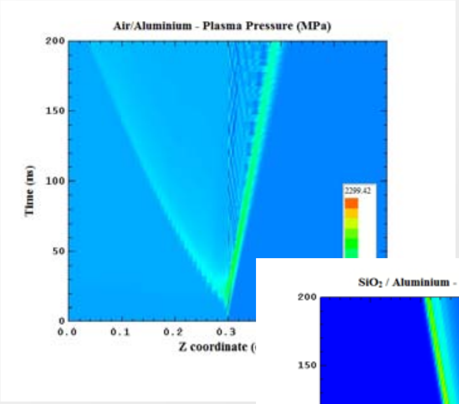


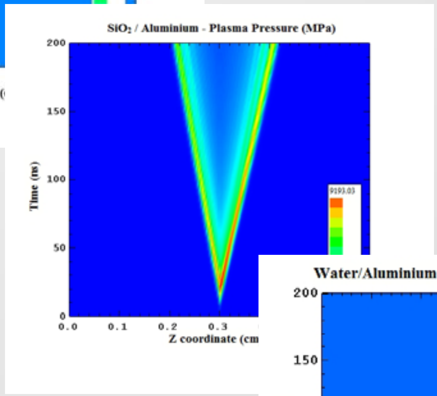
4. NUMERICAL SIMULATION RESULTS

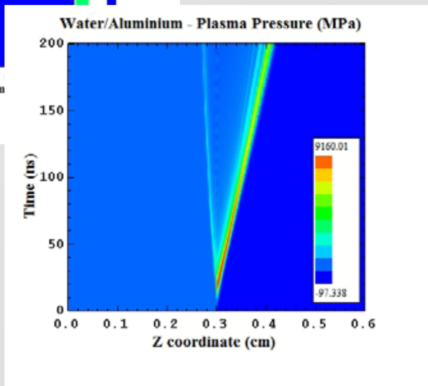
HELIOS Analysis of relative influence of confining material







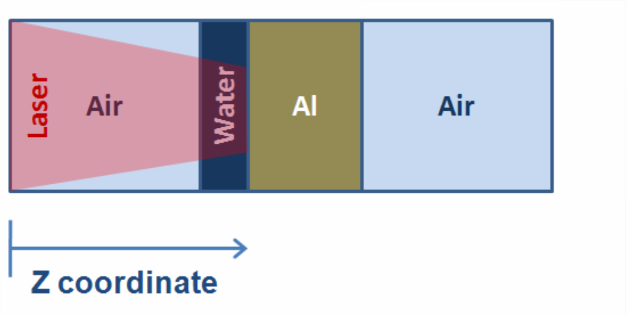


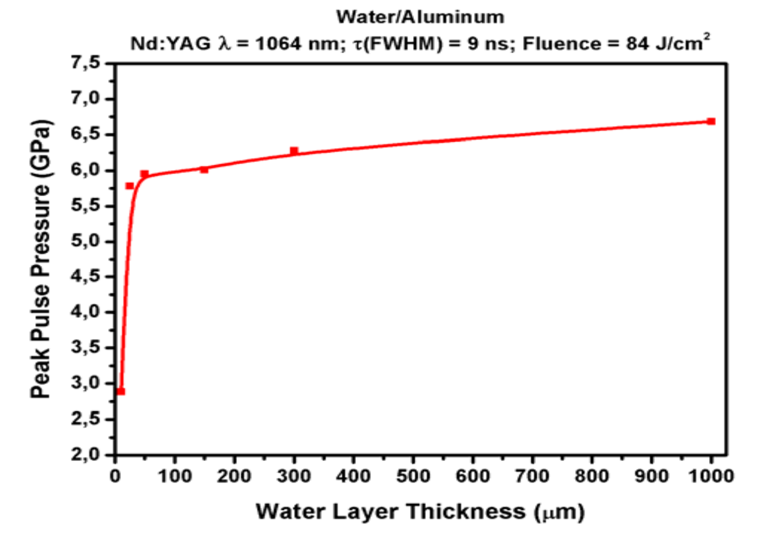


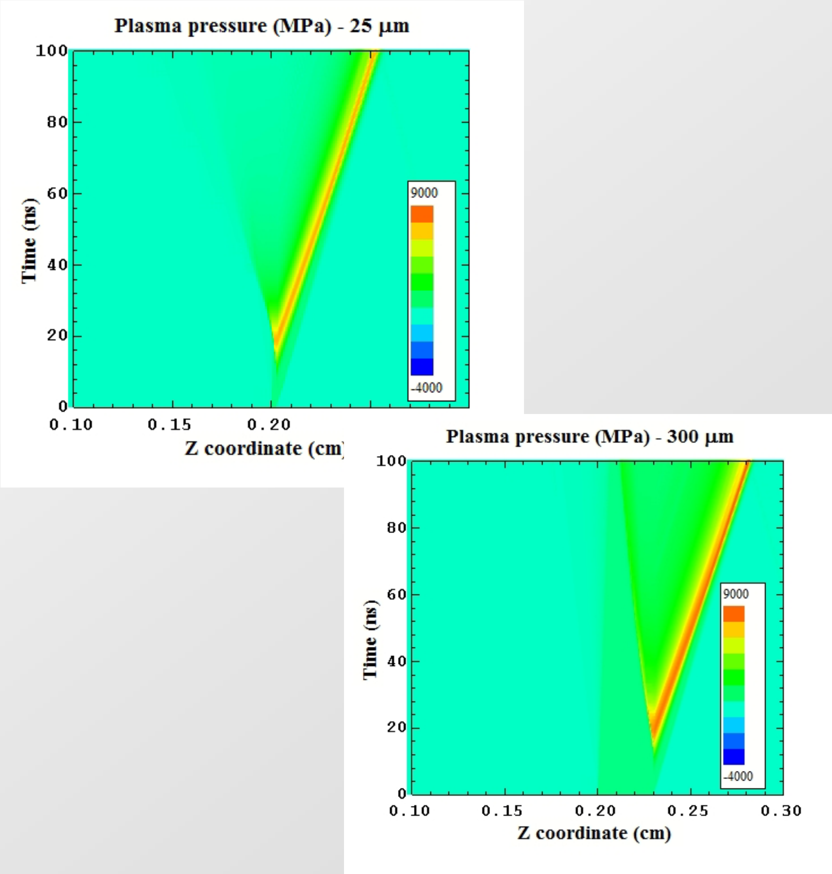
4. NUMERICAL SIMULATION RESULTS

HELIOS

Analysis of influence of water layer thickness



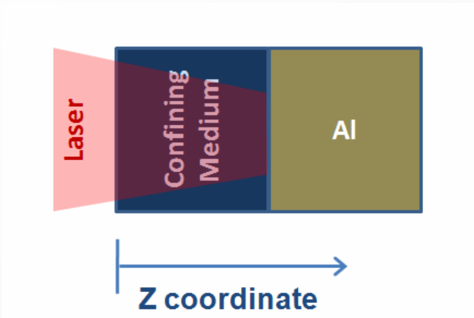


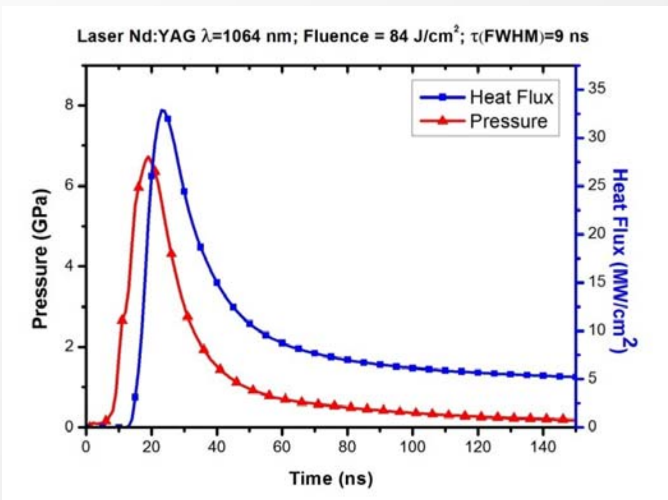


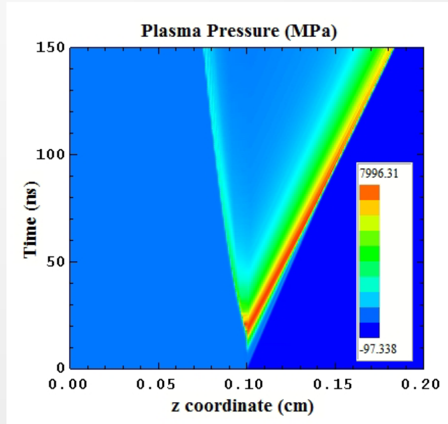
4. NUMERICAL SIMULATION RESULTS

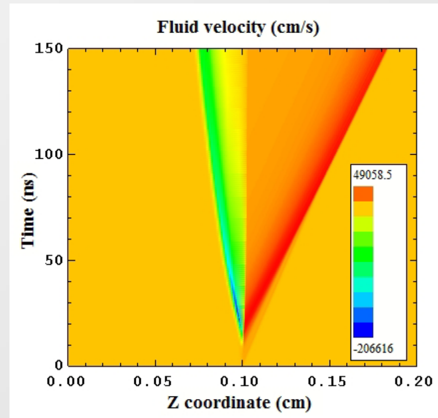
HELIOS

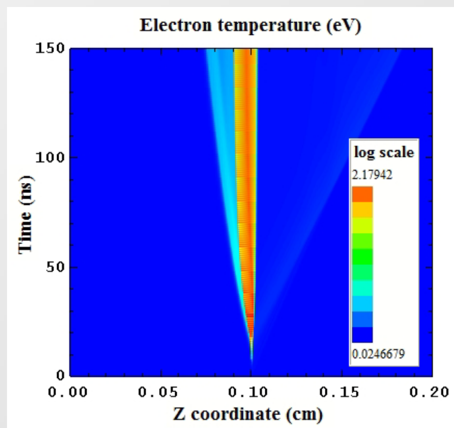
Analysis of plasma for LSP conditions

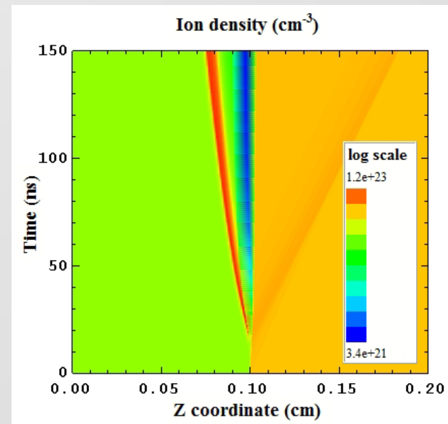












5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

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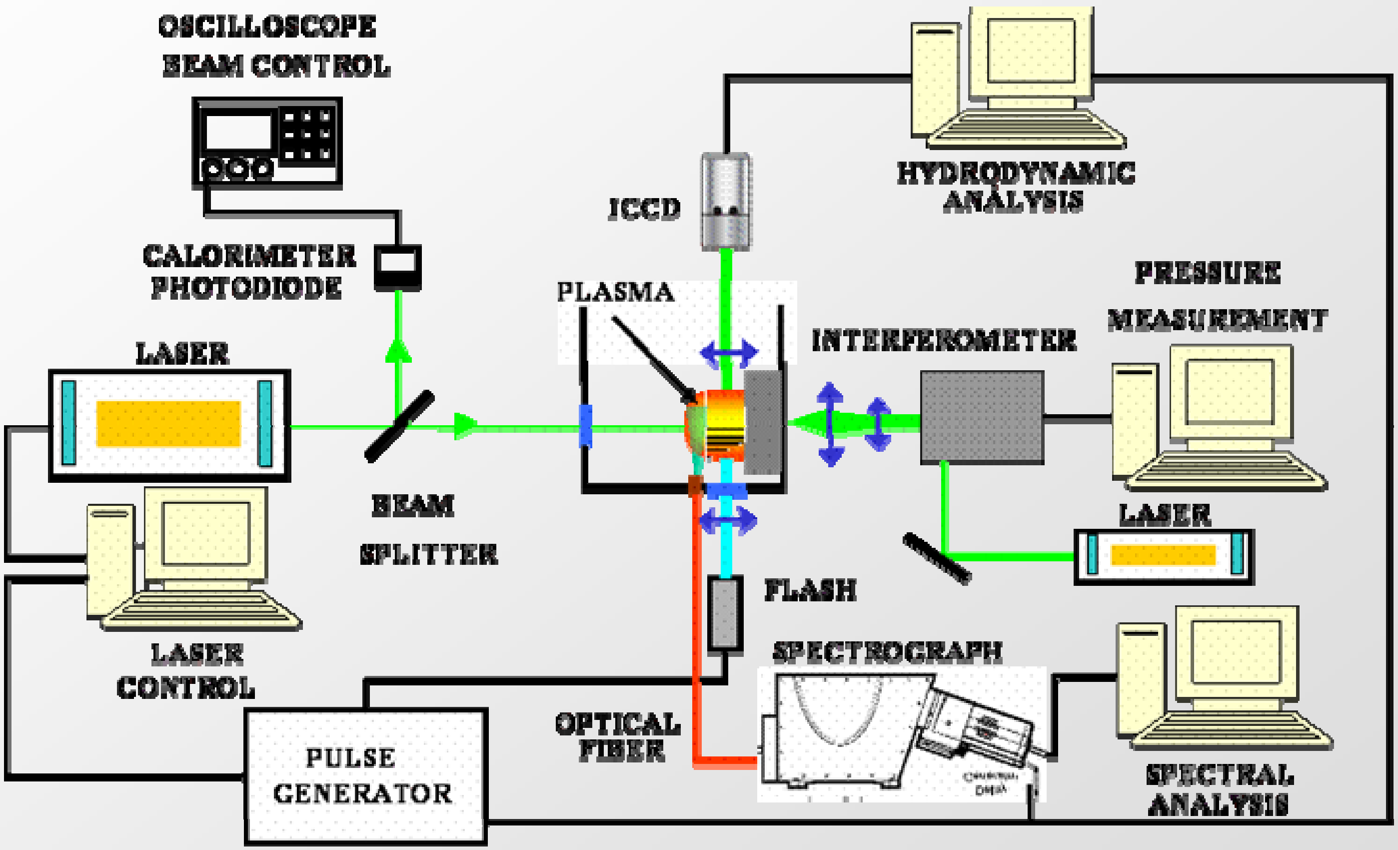
Summary of correlated experimental observations and simulation results defined for plasma monitoring and process design

PLASMA EXPLORED CHARACTERISTICS	EXPERIMENTAL OBSERVATION NEEDED	MATCHING SIMULATION RESULTS
Average plasma ionization energy in interaction region	Line Spectroscopy (integrated spectrum energy)	HYDRA ionization model results
Average plasma density and temperature in interaction region	Line Spectroscopy (collisional line broadening)	HYDRA hydrodynamic simulation
Space resolved plasma density	Shadowgraphy + Schlieren photography	HYDRA hydrodynamic simulation
Shock wave generation and plasma expansion speed	Shadowgraphy + Schlieren photography	HYDRA (short times) + LSPSIM free surface evolution simulation
Breakdown in confining medium	Line spectroscopy	Dielectric breakdown evaluation module in LSPSIM

5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM



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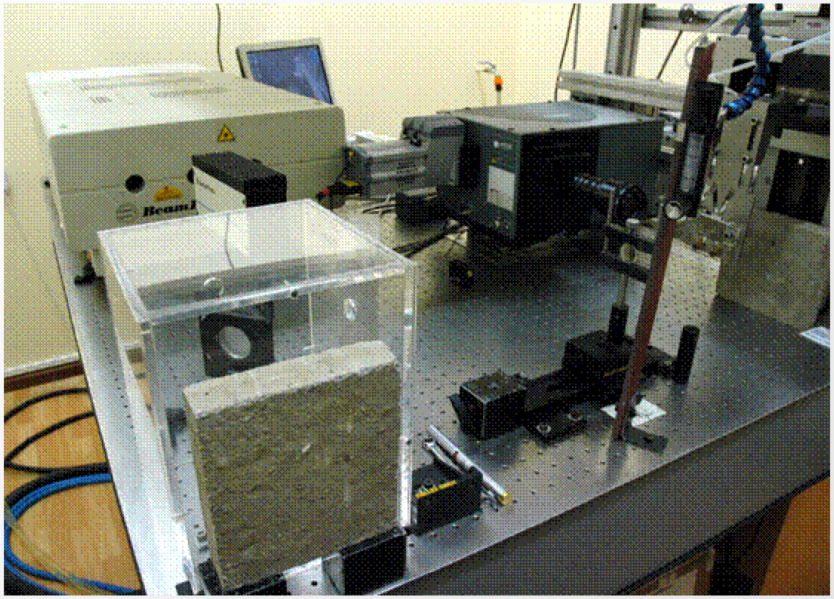

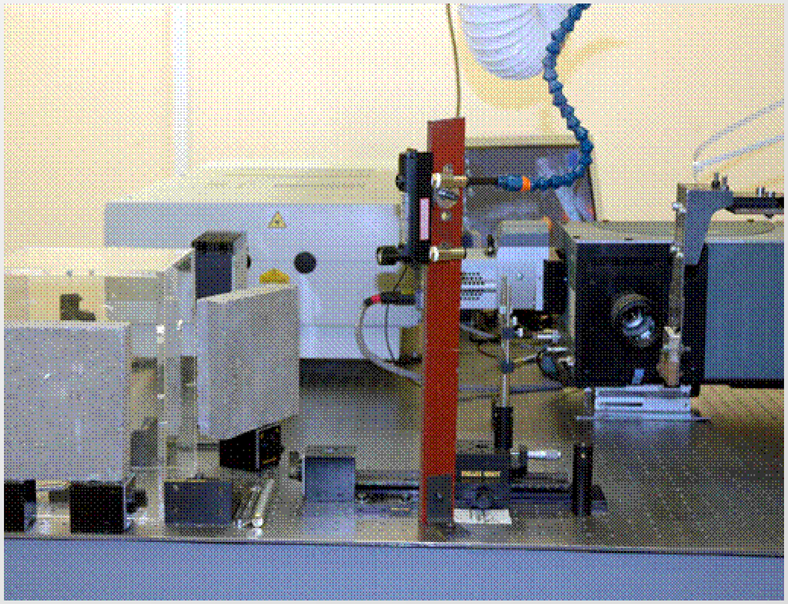

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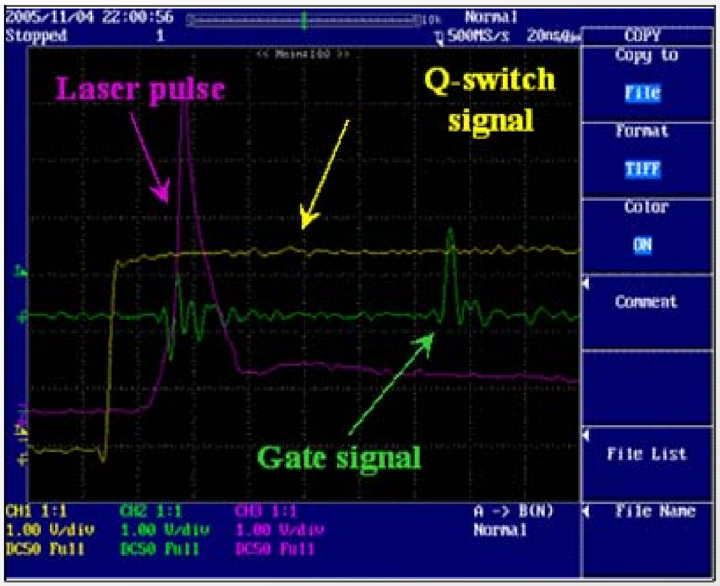
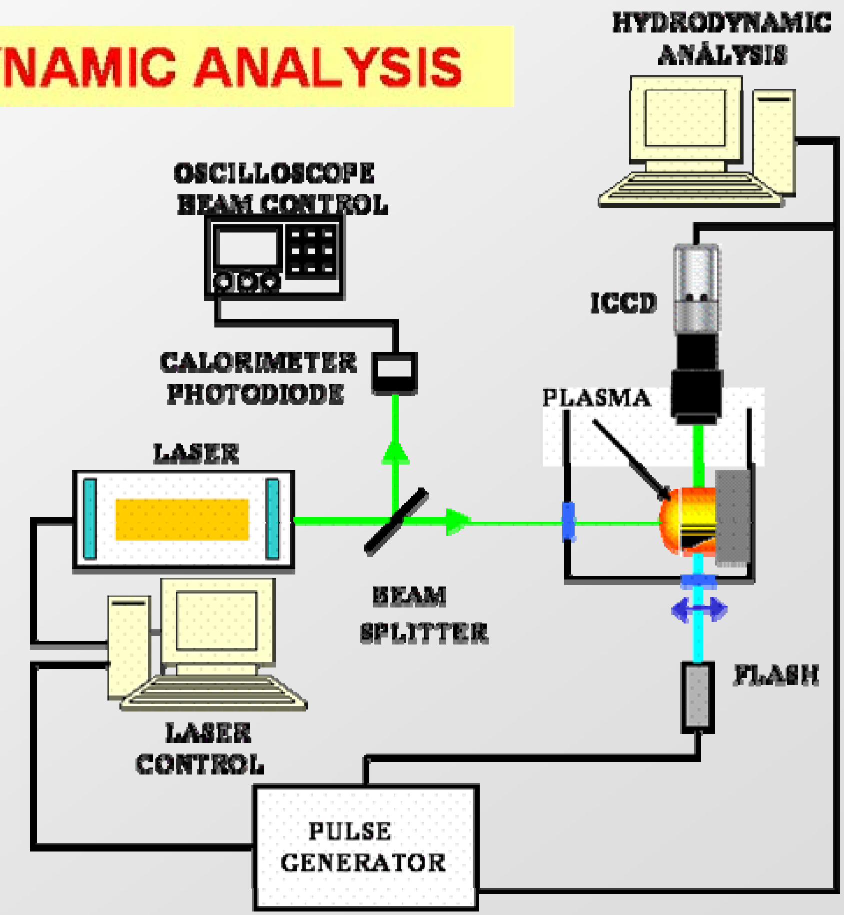
DIRECT IMAGING - HYDRODYNAMIC ANALYSIS





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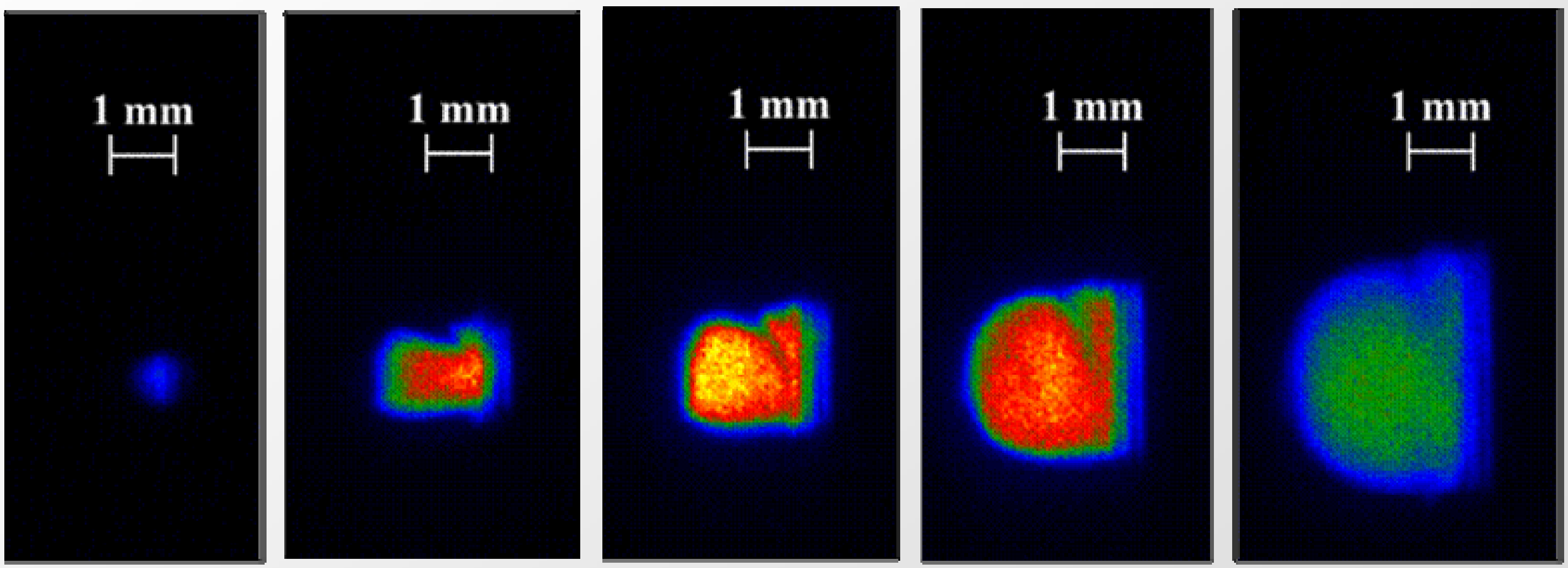
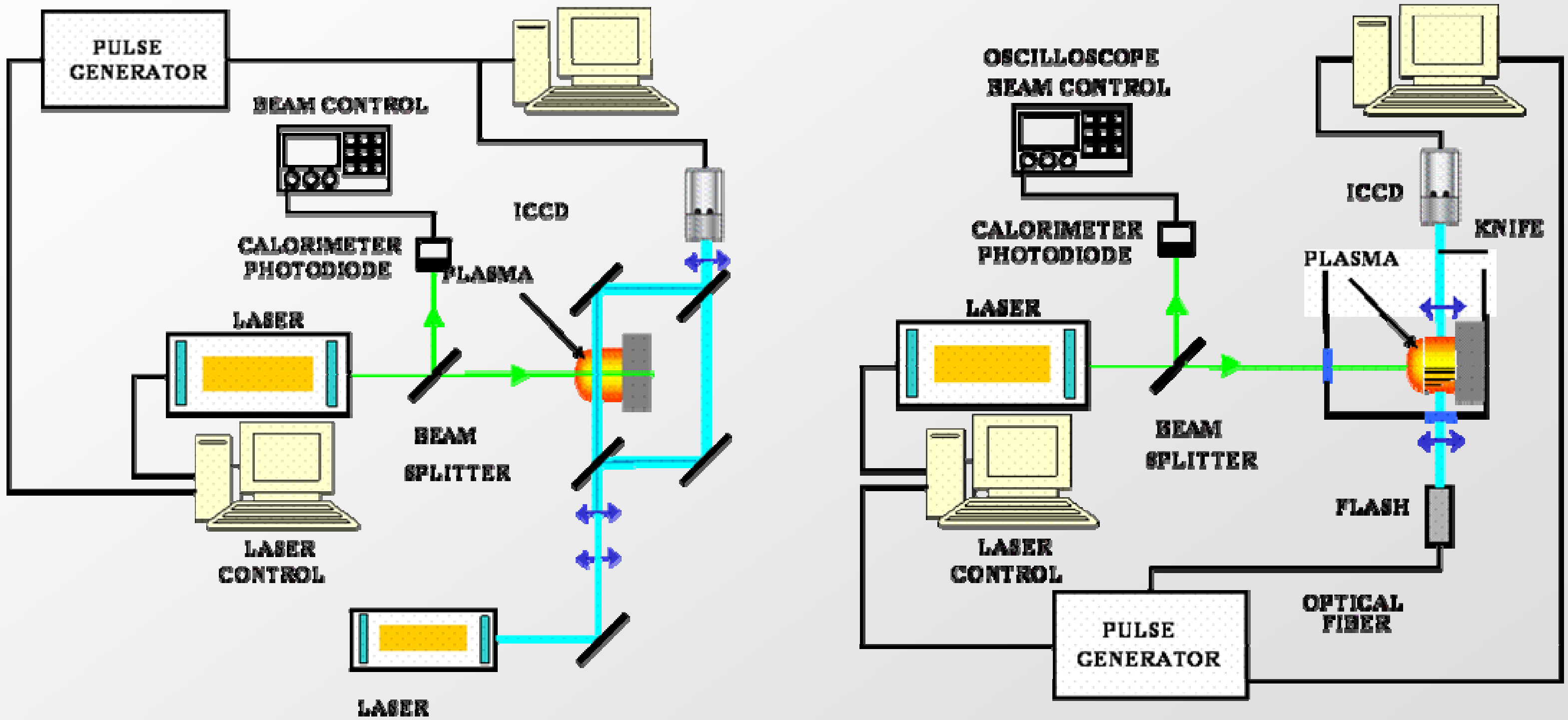


t = 10 ns   t = 25 ns   t = 50 ns   t =100 ns   t =200 ns

5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY



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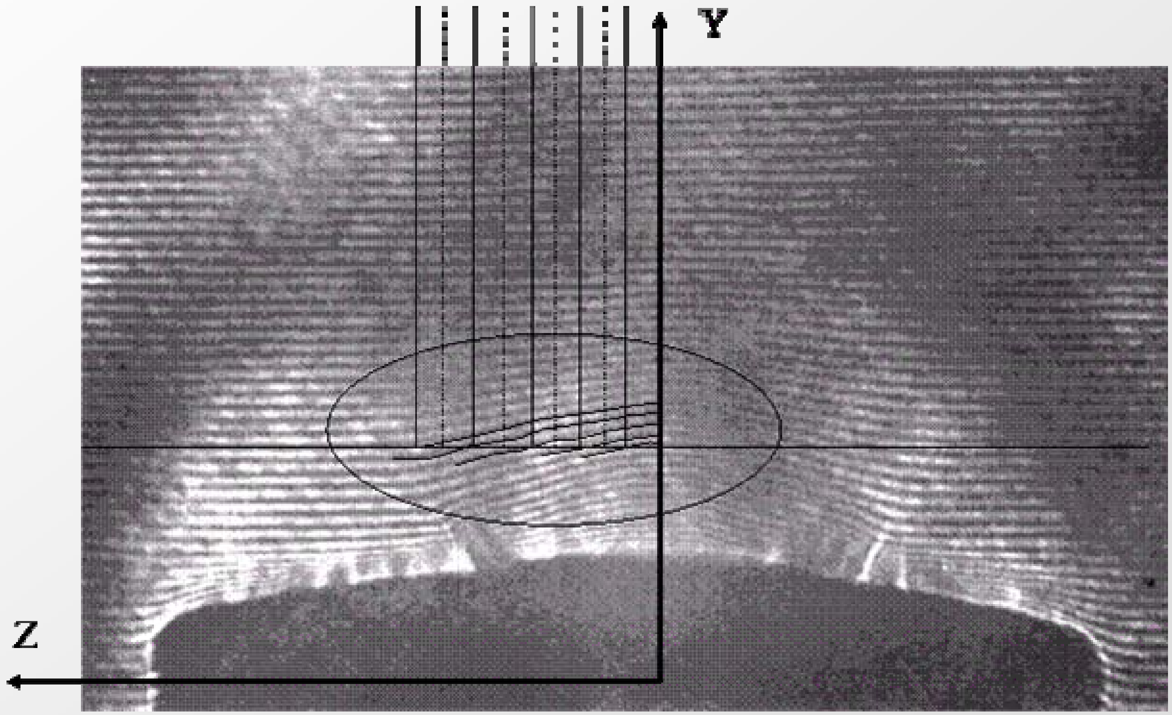

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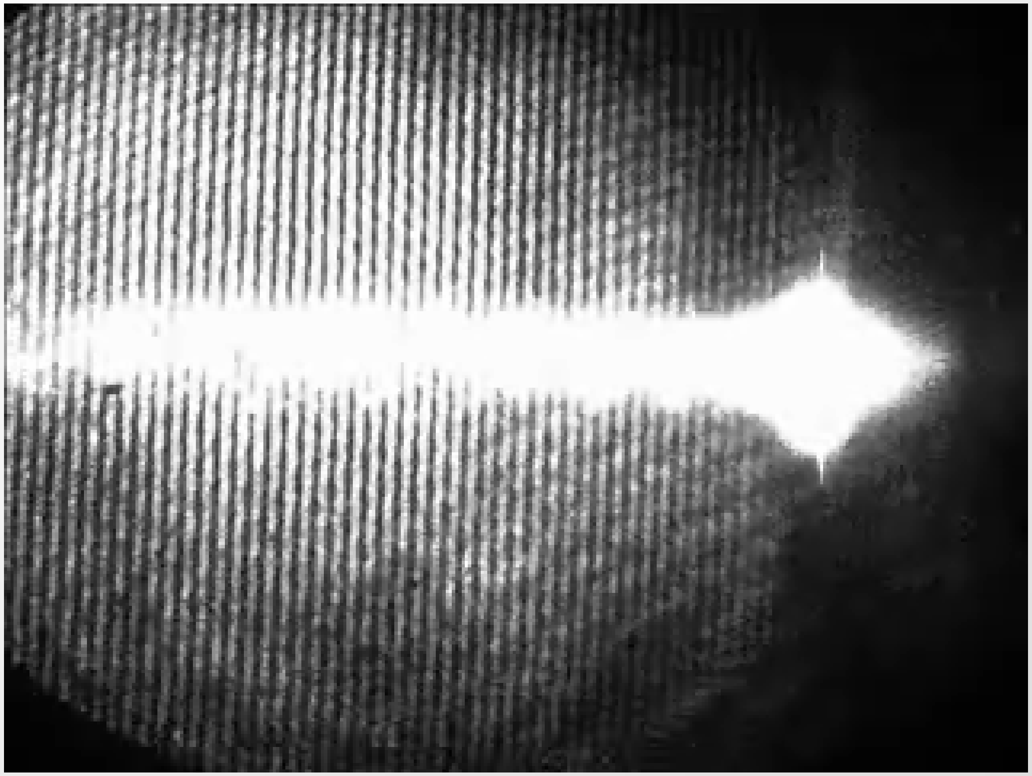
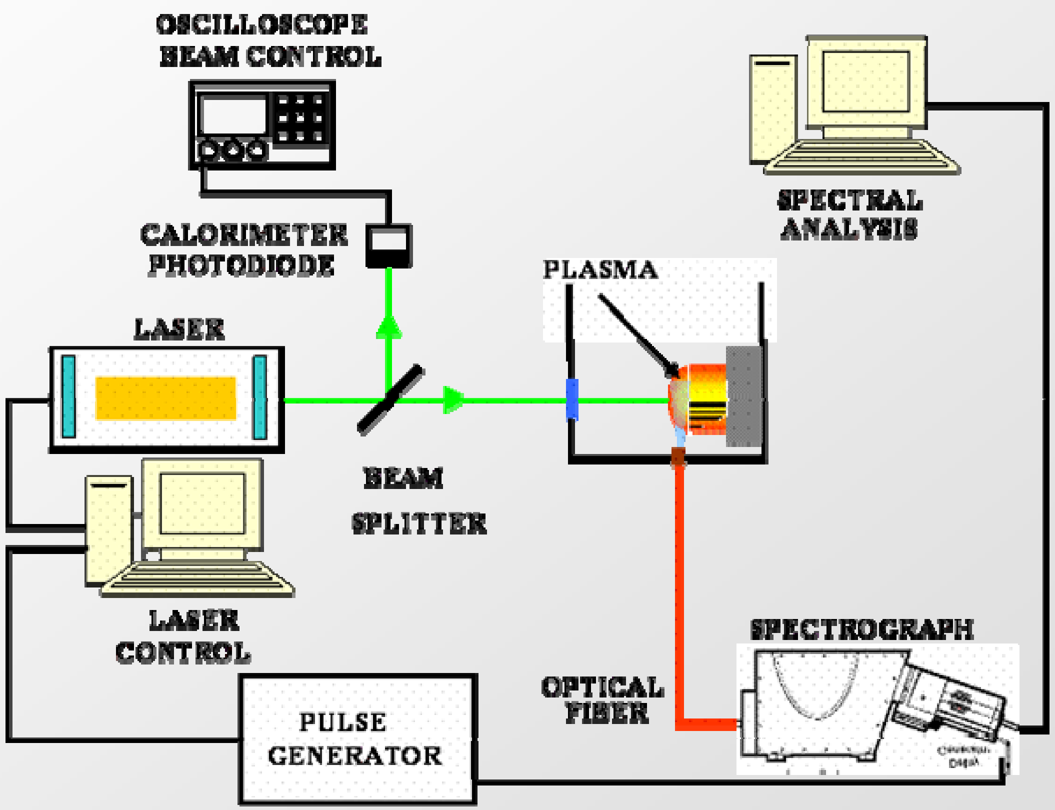


5. EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

EMISSION SPECTROSCOPY



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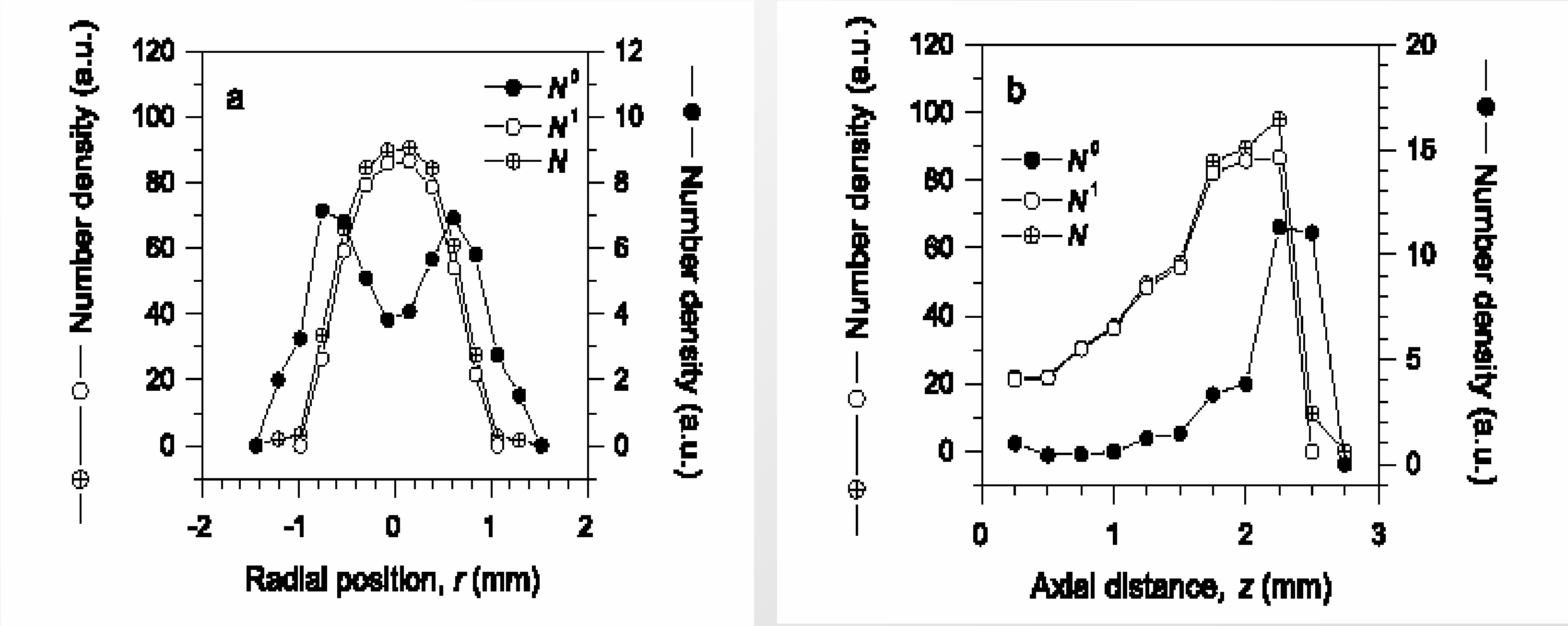

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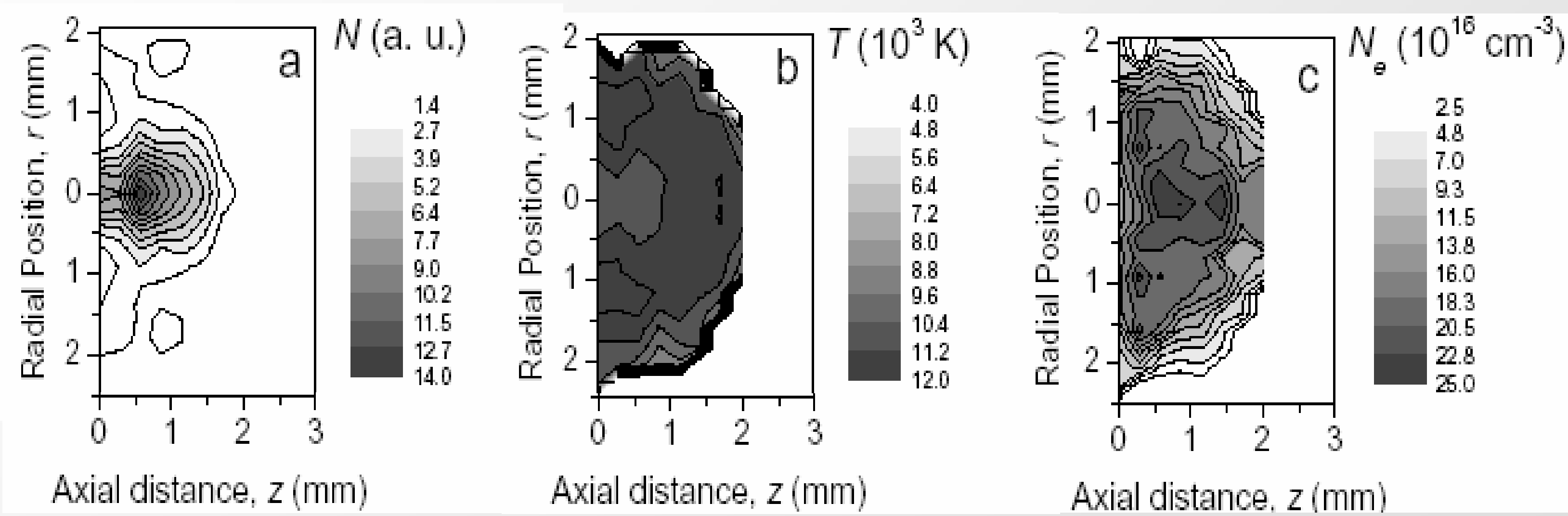
EMISSION SPECTROSCOPY



6. DISCUSSION AND OUTLOOK

- The need for a practical capability of LSP process control in practical applications has led to the development of comprehensive theoretical/computational models for the predictive assessment of the complex phenomenology involved.

- High intensity laser-plasma interaction has revealed itself as a critical point for a proper process understanding and predictive assessment.

- A physically comprehensive calculational model (SHOCKLAS) has been developed able to systematically study LSP processes starting from laser-plasma interaction. The integrated laser-plasma analysis routine, based in realistic material EOSs, provides a unique capability for process coupled theoretical/practical characterization

- The development of the appropriate experimental diagnosis facilities enables a reliable process predictive assessment capability in view of process industrial implementation.

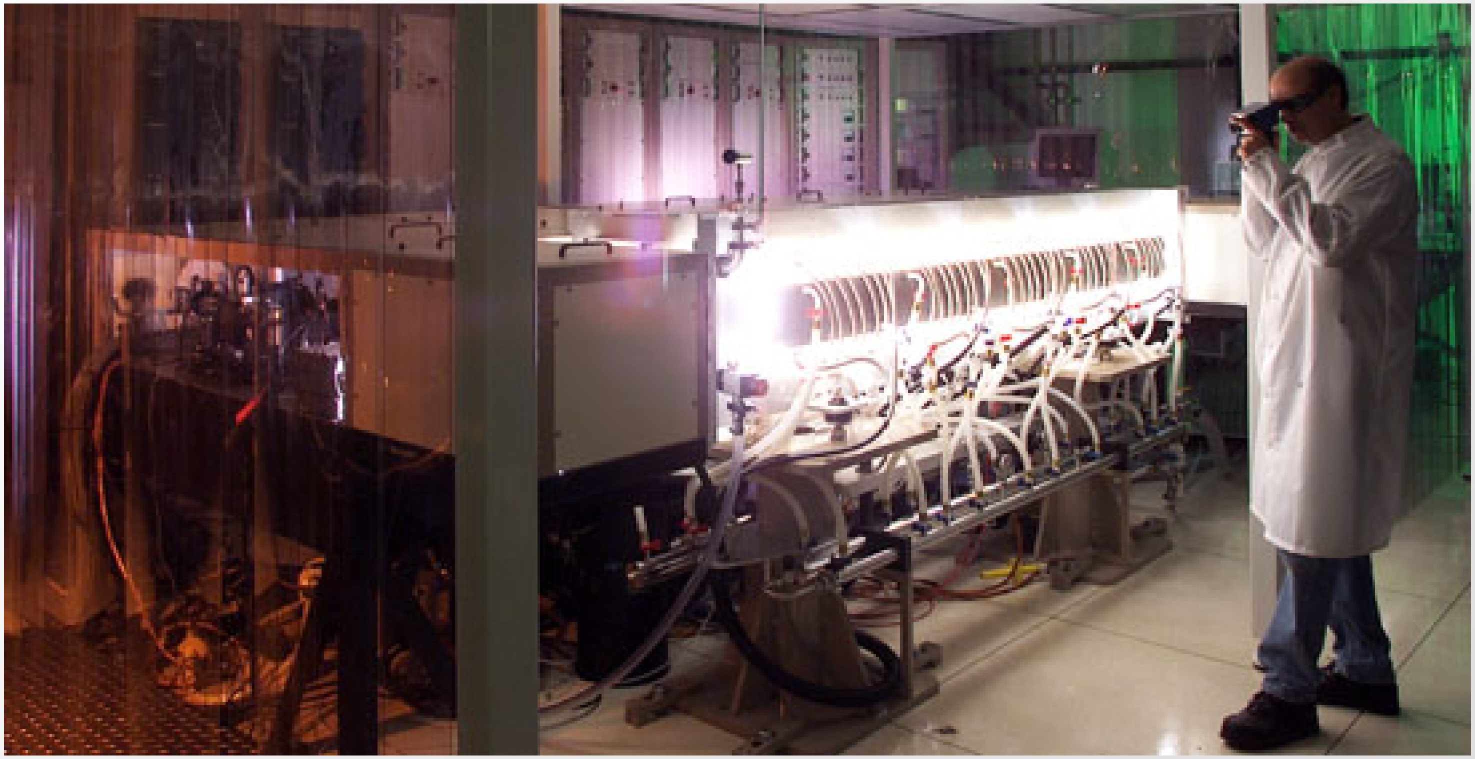
6. DISCUSSION AND OUTLOOK

- The upgrading of LSP experiments to industrial production requires the development of advanced laser sources combining high peak intensities, pulse energies and repetition rates. This is nowadays a major challenge to laser systems developers.

- The analysis and characterization of laser-matter interaction at high intensities and short times in the frame of development of industrial applications provide a first rank occasion for both basic and applied research.

- Laser Shock Processing, together with other very high intensity laser applications is considered to provide a unique present-day bridge to the high intensity ultra-short time developments envisaged for ELI and, in this sense, experimental facilities in the ns-ps, GW-TW range are considered as valuable subsidiary tools to reach the ELI objectives.

6. DISCUSSION AND OUTLOOK



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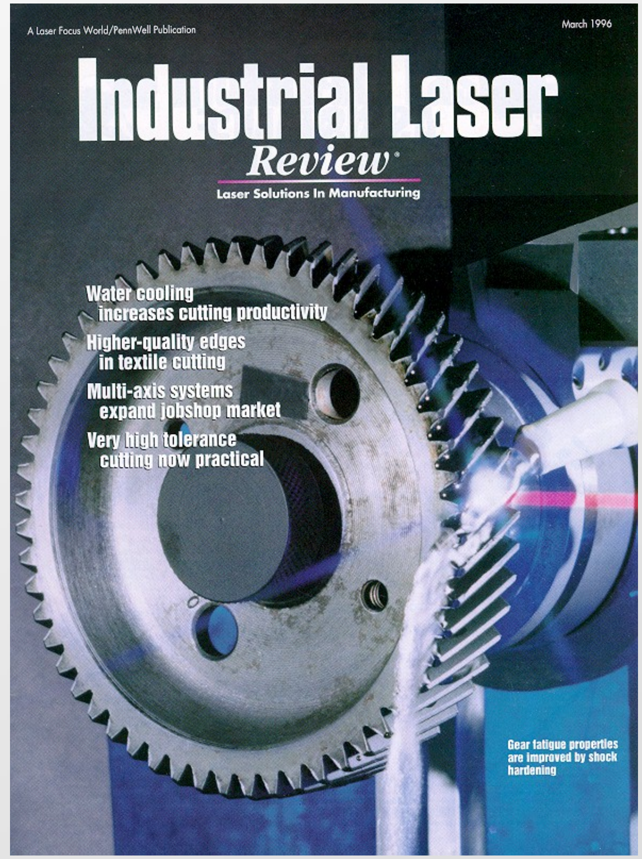

A Laser Focus World/PennWell Publication

March 1996

Industrial Laser Review

Laser Solutions In Manufacturing

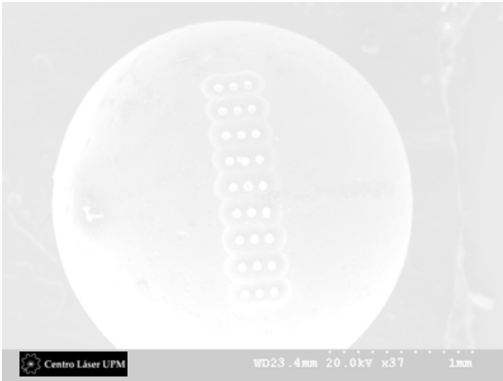
Water cooling increases cutting productivity

Higher-quality edges in textile cutting

Multi-axis systems expand jobshop market

Very high tolerance cutting now practical

Gear fatigue properties are improved by shock hardening



Thank you very much for your attention !

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