# High pressure produced by laser:
## Challenges and limitations

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PHYsique à Haute Densité d'Energie par Laser

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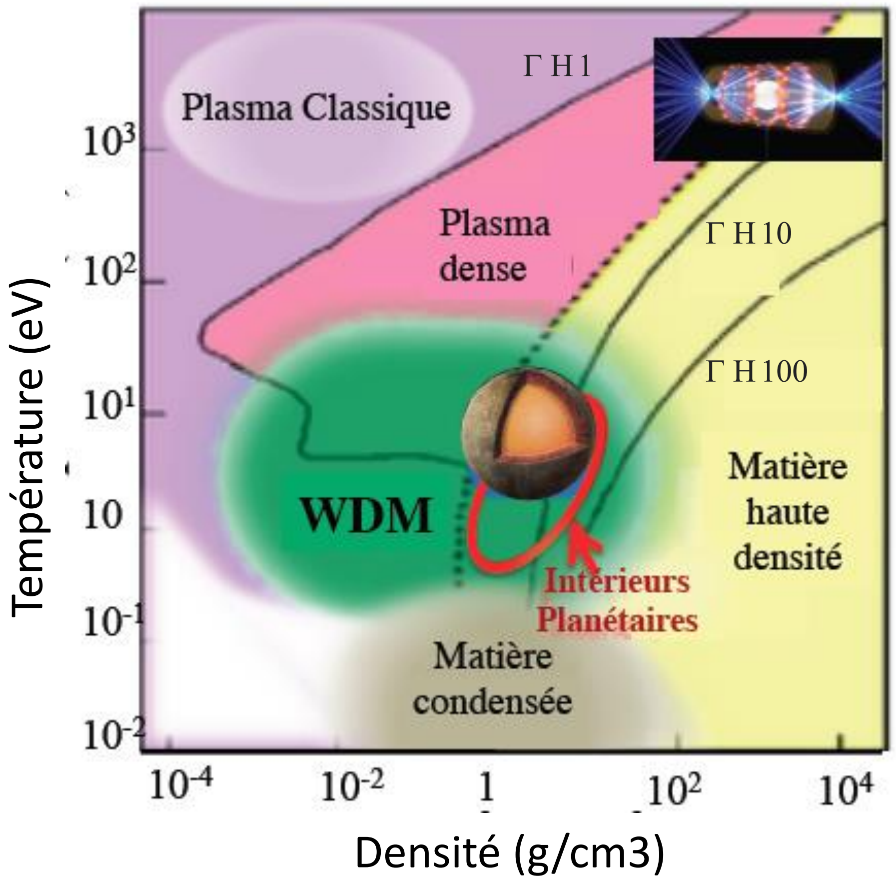
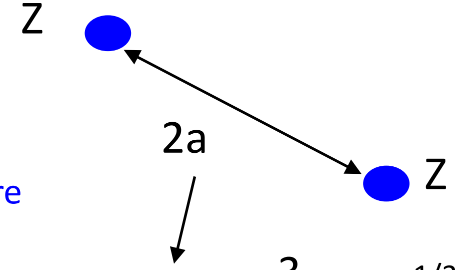
# High Energy density  (HED)-Matter in extreme condition

- Hot Dense Matter (HDM) occurs in:
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly and indirectly driven inertial fusion experiments

- Warm Dense Matter (WDM)occurs in:
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion experiments



# In dense plasmas, the ions are strongly correlated and coupled with complex atomic physics




Ion sphere radius

$$a = \left(\frac{3}{4\pi N_i}\right)^{1/3}$$

Coulomb coupling parameter

$$\Gamma = \frac{(Ze)^2}{a\, k_B T}$$

WDM is the state at the intersection between plasma physics and condensed matter physics.

| Strongly coupled $\Gamma > 1$ |
|---|
| • High $\rho$ and low Te<br>• Non-perturbative methods<br>• No small parameters<br>• No clear distinction between atomic and plasma physics |

$\Gamma_{ii} \geq 1$ **"strong coupling" affects all collisional processes:**

- **particle transport**
- **EOS**
- **opacity**

Theoretically the difficulty is there are no small parameters

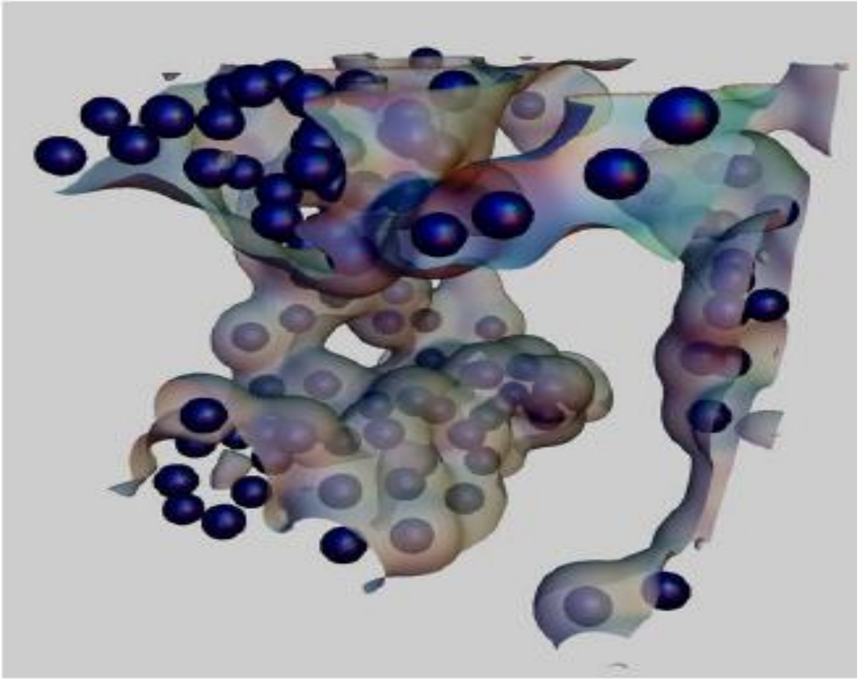
**Little experimental data exist for any plasmas**

**Nearly no data exist in the warm dense regime**

# Important progresses on theoretical Side: Quantum Molecular Dynamics calculations

QMD code

- Pseudo potentials
- Small number of bands
- Small number of k-points
- Ionic trajectories



Fluctuation-dissipation theorem coupled with QMD calculations provides a consistent approach of the structure & transport properties in dense plasmas

- Equation of State
- Transport properties
- opacities….

Desjarlais *et al.*, Phys Rev E 66 (2002)
Recoules *et al.*, Phys Rev E 66 (2002)

# How do we get High energy density conditions ?

**By Compression**

Static techniques

Diamond Anvil Cell

ISOTHERMAL COMPRESSION

$P \approx 0$ - a few Mbar

$T = T_0$

$\rho > \rho_0$

**By Compression and Heating**

Dynamic techniques

Gaz guns

Chemical explosive

**High power lasers**

SHOCK COMPRESSION

$P \approx 0$ - hundreds of Mbar

$\rho > \rho_0$ T up to 10-20 eV

**By Heating**

Ultra fast beam

ISOCHORING HEATING

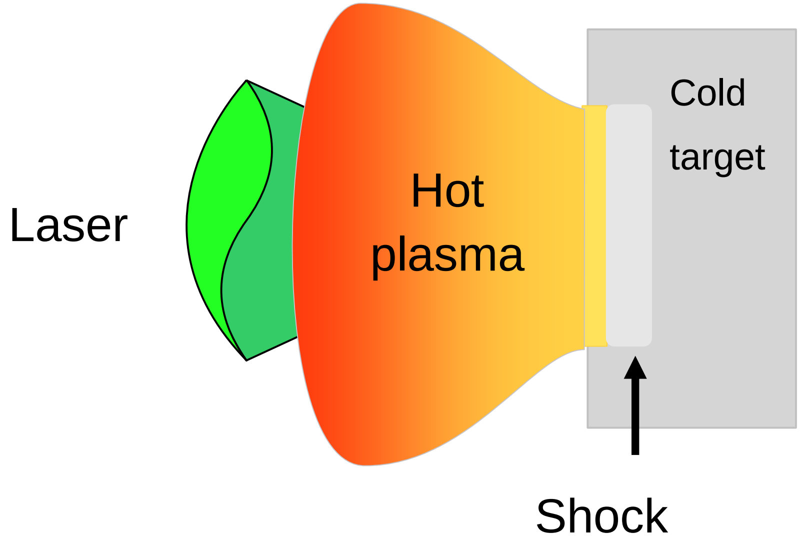
Patel et al PRL (2003)

$T \approx$ 10-100 eV

$\rho \approx \rho_0$

The most extreme conditions are achievable by *laser shock compression*

# Laser driven shock wave



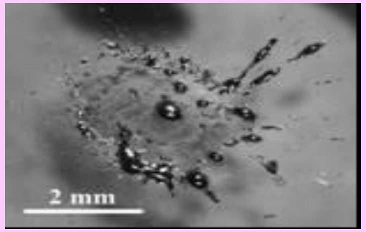

**Laser rapidly heats ablator creating a rocket like effect**
**Ablation pressure**

$$P \approx 12(I_L/\lambda)^{2/3}$$

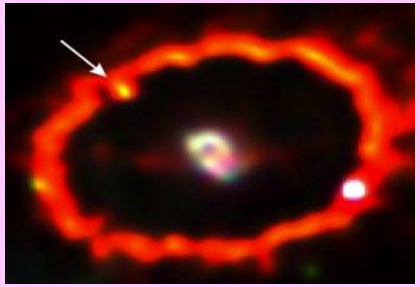
**$I_L$ en $10^{14}$ W/cm$^2$**
**$\lambda$ en µm**
**P en Mbar**

Large pulse of focused light
- Energies > 1 kJ
- $\lambda$ : usually 527 or 351 nm
- 1 – 10 ns pulse duration
- Sample dimensions ~ 1 mm dia, 50 µm - 100 µm thick
- Focused intensities range from $10^{13}$ – $10^{15}$ W/cm$^2$
- Dynamic pressures range from 1 – 80 Mbar

# laser-induced shock




material processing: debounding under laser shock of adhesive coating – ejection of microdroplets

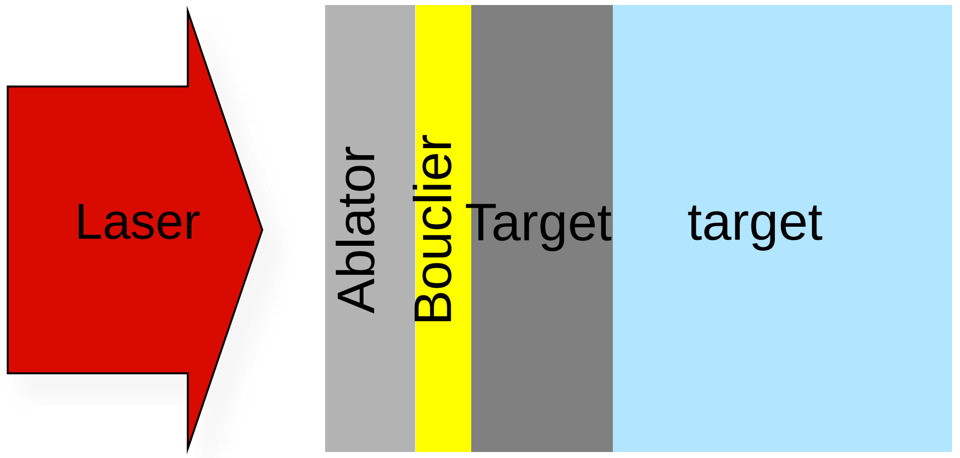


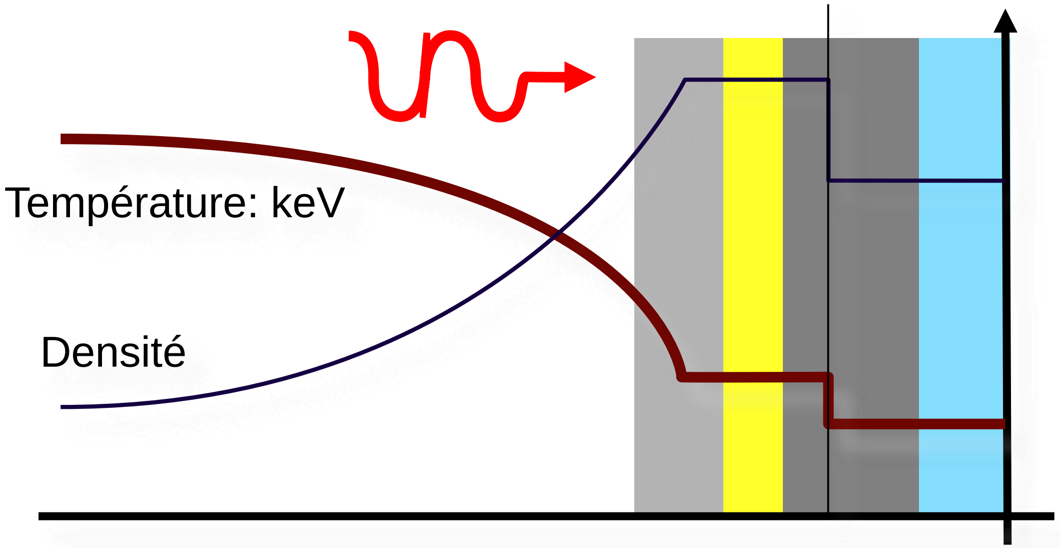
laser-driven shocks: an opportunity to study planetology & astrophysics in the lab.

Study:

- Material properties at extreme P
- Structural & electronic properties
- Existence and properties of new materials

# Structured target needed




Problems to be solved

X-rays and particles are emitted from hot plasma ⇨ Preheating

To mitigate Preheating

Use 2w laser to decrease fast particle in corona α $I\lambda^2$

Use high Z layer to absorb X-ray

Non uniform focal spot ⇨ Non uniform front shock

adaptative optics and random phase plate

Thickness of the ablator to smooth

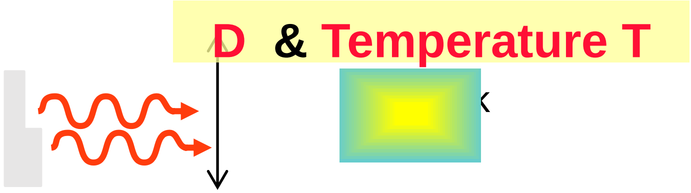
high frequencyfluctuation

# Diagnostics

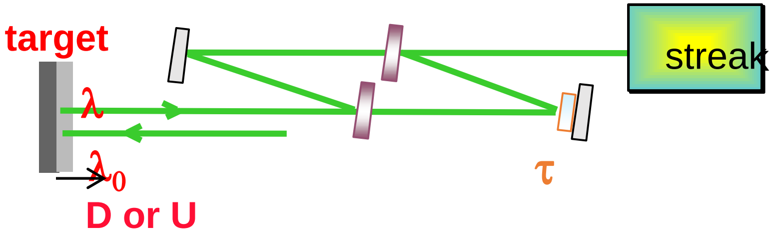
Usual Shock diagnostics

Measure of particle and shock velocity with visar ans SOP

**Self-emission**




**Velocity Interferometer System for Any Reflector (VISAR)**




**Velocities (D or U) by Doppler effect & reflectivity**

Using X-ray diagnostics

Development of *microscopic* studies to investigate finely WDM structure changes, phase transitions and to test approximations used in theories

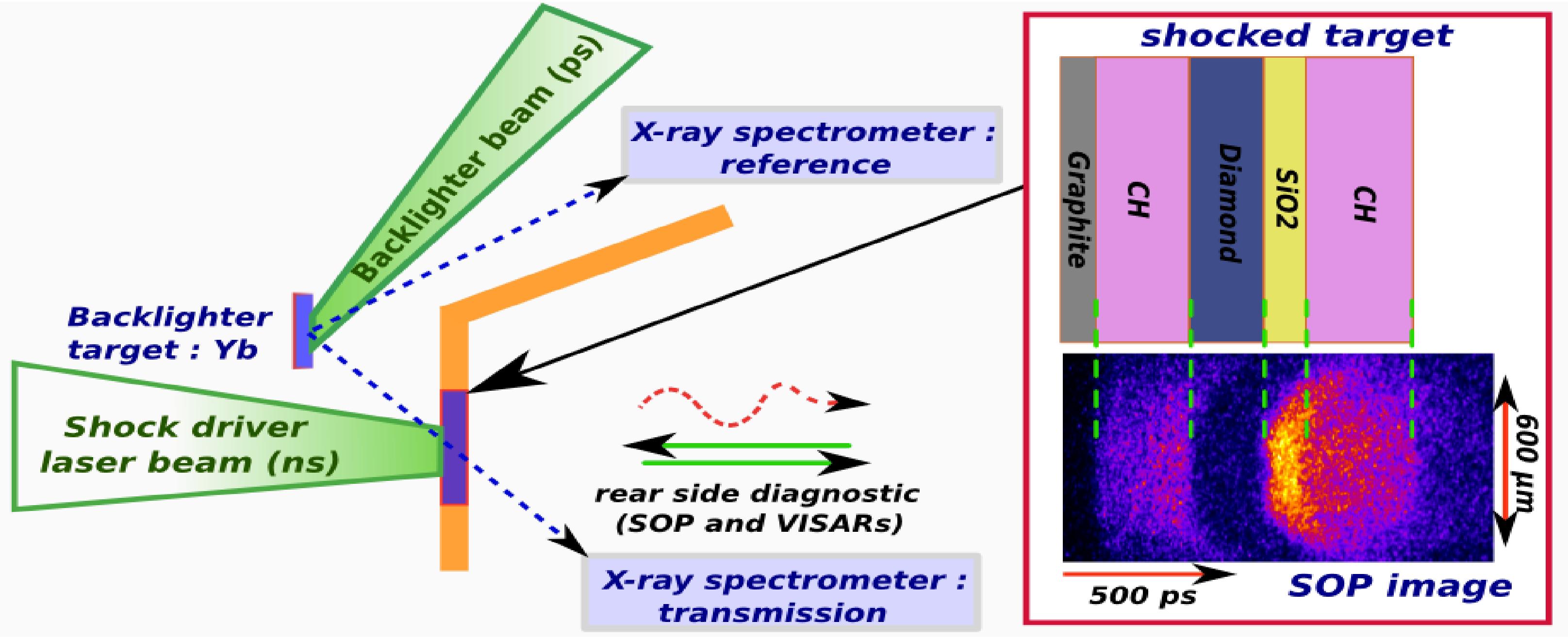
- X-ray scattering
- X-ray diffraction
- X-ray absorption near edge spectroscopy

# XANES on $SiO_2$ : LULI2000

SUPPORTED BY ANR

PLANETLAB

Probe the evolution of the SiO2 electronic and ionic structure as function of a large domain, well controlled, uniform and extreme density and temperature conditions




**LASER SHOCK**

- HPP Phase plates
- Well-designed target geometries

**Independant Visible diagnostics**

- VISARs
- SOP

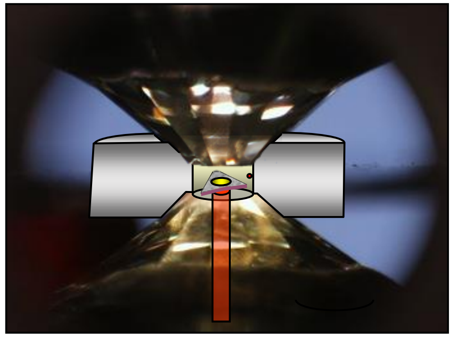
**•Time-resolved XANES diagnostic**

- 2 X-ray spectrometers
- A broad-band X-ray ps source

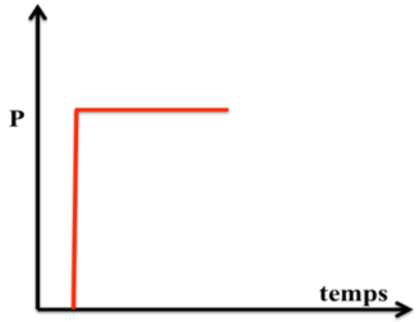
X--ray absorption near edge spectroscopy (XANES) is a powerful diagnostic To study structure changes, phase transitions and to test approximations used In theories

A. Denoeud *et al.,* Phys. Rev. Letter **113** (2014)

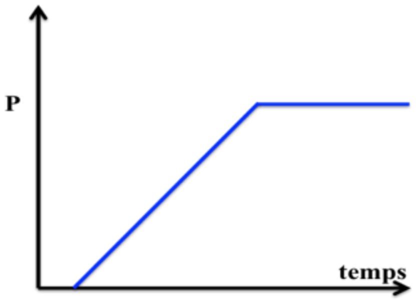
# To study larger regions of phase diagram

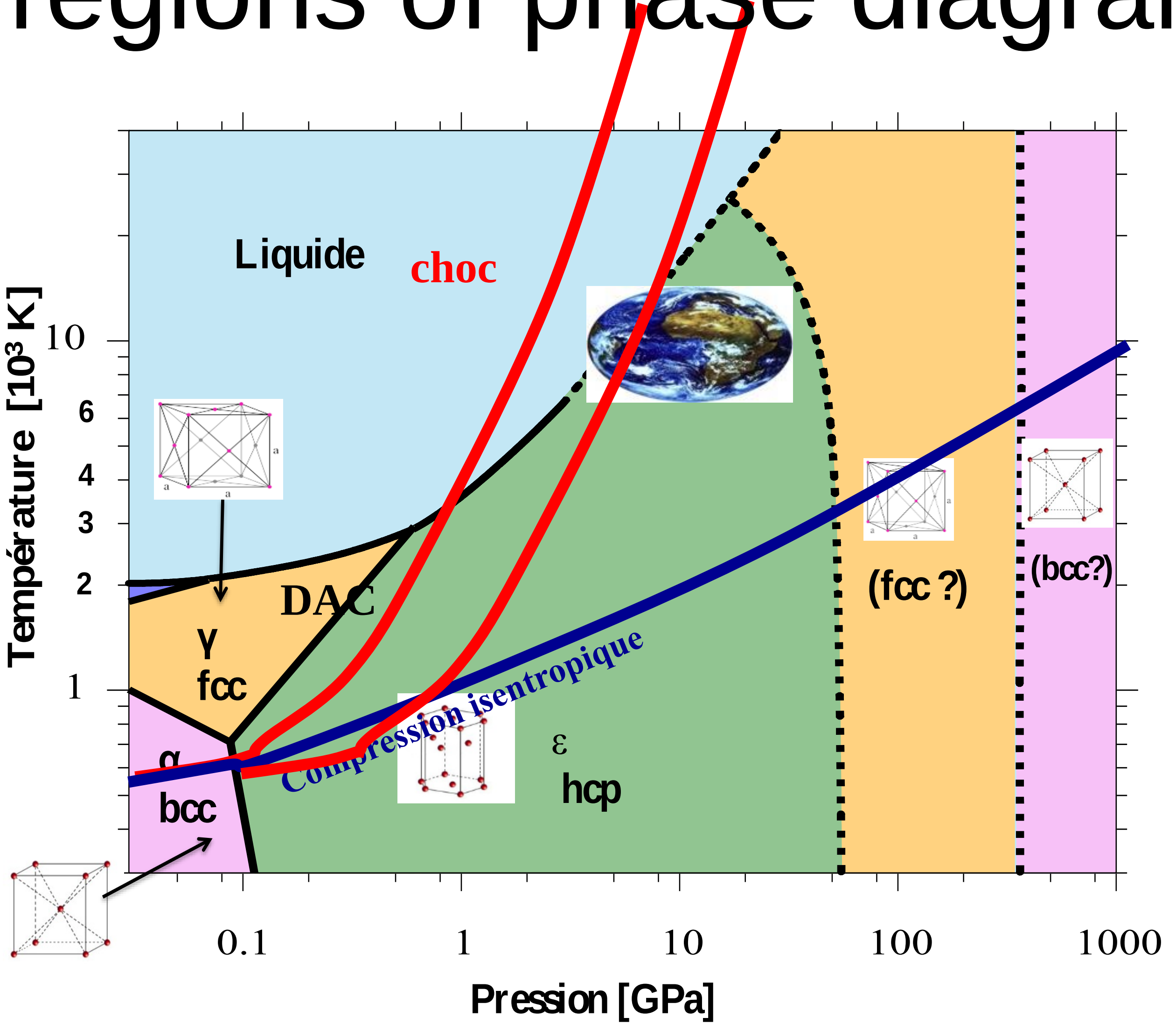


Choc




Compression isentropique (C.I)



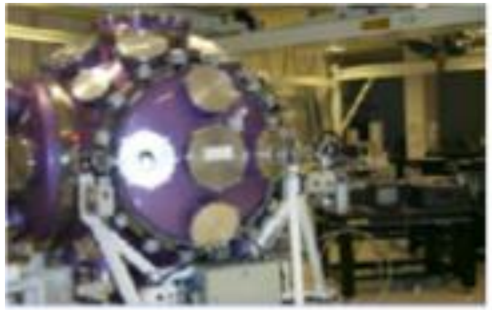

- Development of compression techniques using
  - Quasi-isentropic compression
  - Shock on precompressed targets
  - Double shock technique

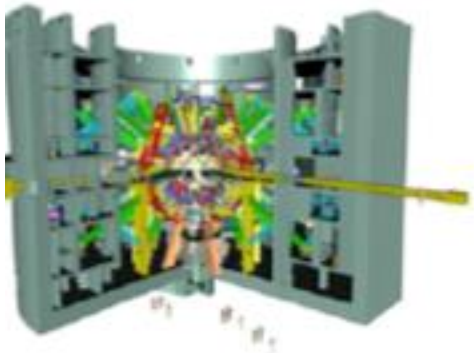
# High energy >1kJ open laser facilities

Energy

- PALS – Prague - Czech republic
- Janus laser – LLNL- USA
- Vulcan- RAL- UK
- LULI2000 – Ecole Polytechnique France
- GEKKO laser- Osaka University Japan
- OMEGA laser University of Rochester USA
- LMJ/Petal – CEA – France
- NIF laser LLNL USA

- Only few shots a day possible

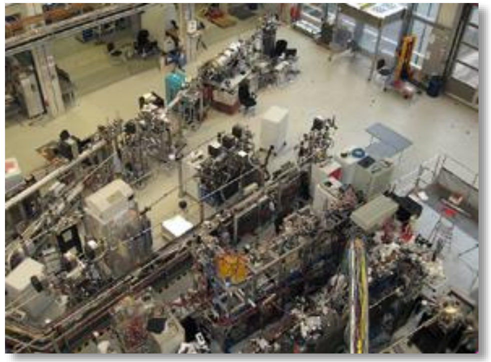




# X-ray light sources

- FEL facilities with optical laser
  - LCLS SLAC, Stanford, CA
    - 3 J – 40 fs UHI laser - 2× 12 J – ns HE laser
  - SACLA Spring-8 Harima, JAP
    - 2 × 8 J – 40 fs UHI laser - 400 J – ns HE laser
  - European XFEL Hamburg, GER
    - 1 mJ – 15 fs – MHz laser - 4 J – 40 fs UHI laser - 100 J – ns HE laser
- Large users community - high repetition rate –Operation 24/24 7/7
- New opportunity to study matter in extreme condition

*FLASH - XFEL - DE*



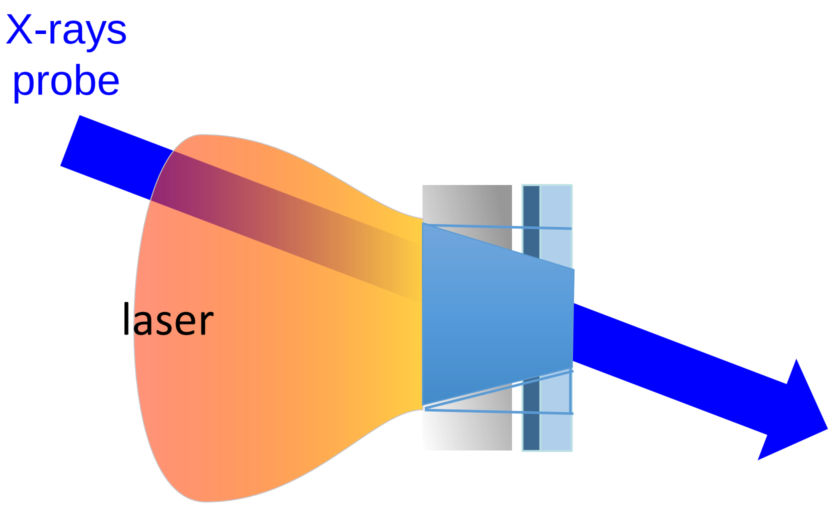
*LCLS - USA*

*SACLA - Japon*

# Experimental needs

- Versatile reliable high energy laser drivers
- Uniform pressure distribution
  - controlled using phase plates and deformable mirror
- Steady pressure pulse
  - precise pulse shape control
- Control of initial conditions
  - Preheat mitigation 2W and well design multi layer  target
- High precision measurement diagnostics
  - Shock diagnostics
  - X-ray probe techniques to  access to microscopic structure

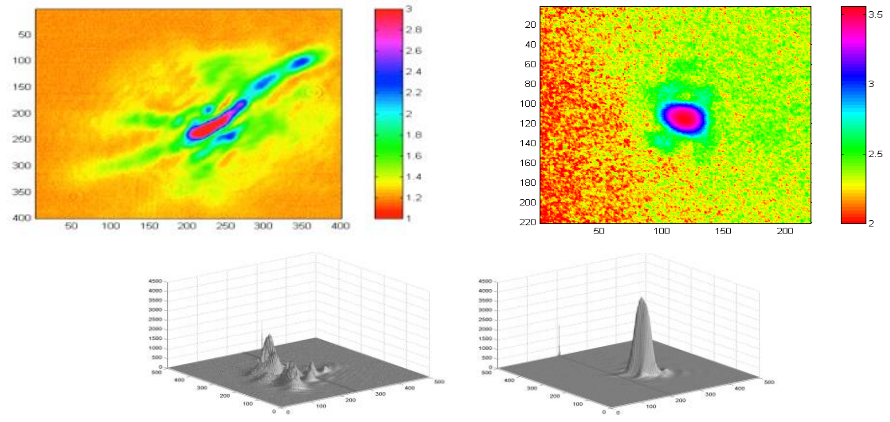
# Spatial Extent of shock

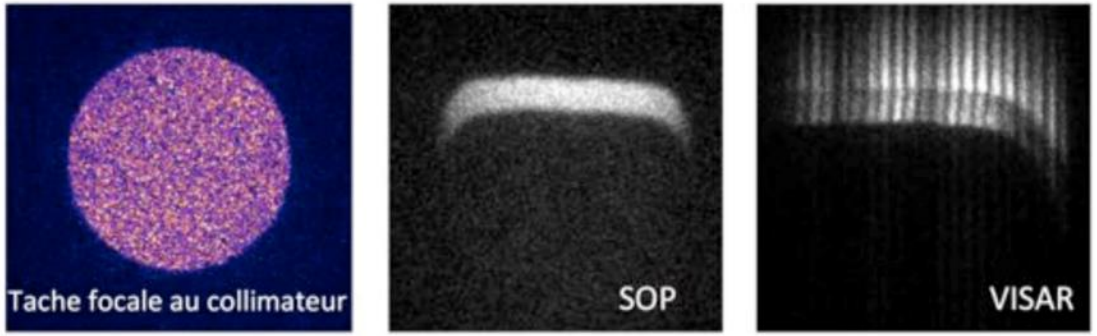



- We need to consider the final spatial extent of planarity of the compression wave due to the refaction wave on the side.
  - Decrease the surface for the Visar measurement
  - Alignment of the x-ray probe needs to take into acount the decrease of the surface function of sample thickness
- Implies large focal spot to insure visar and X-ray measurement

# Uniform pressure distribution

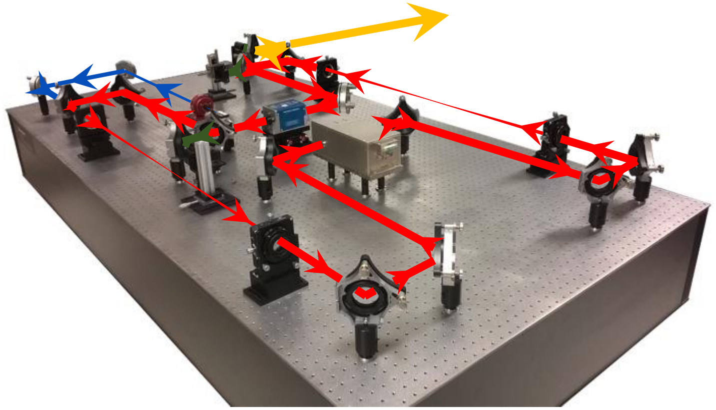
- Obtained using
  - adaptative optics
    - active laser phase correction combining
      wavefront sensor, deformable mirror & convergence loop
  - Random phase plate
    - 250µm to 2 mm Ø



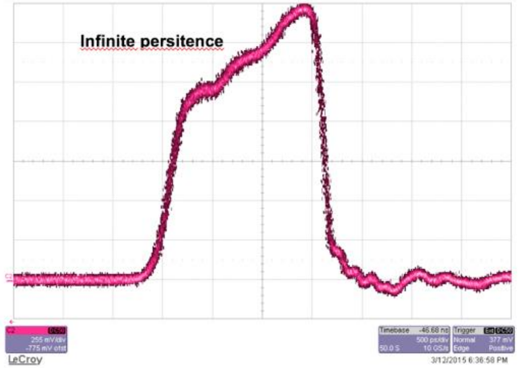


# New development of Laser Oscillator

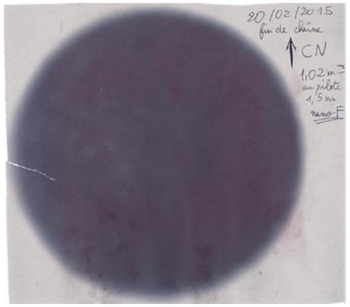
Breadboard 2400 x 1250 mm



Long term stability front end output




1,3 % RMS over a day
Jitter <10 ps (TTL to optical)

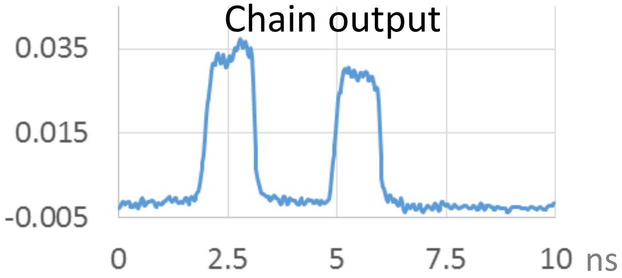


Implemented at LULI200
febuary 2015

Fiber Front end and regen amplifier allow pulse shaping and stability

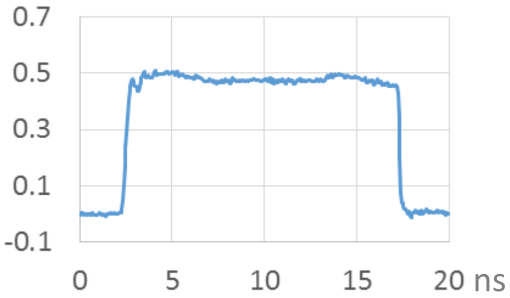
# Different time profile obtain with the fiber oscillator

Double ns pulses **1ns/2ns/1ns**



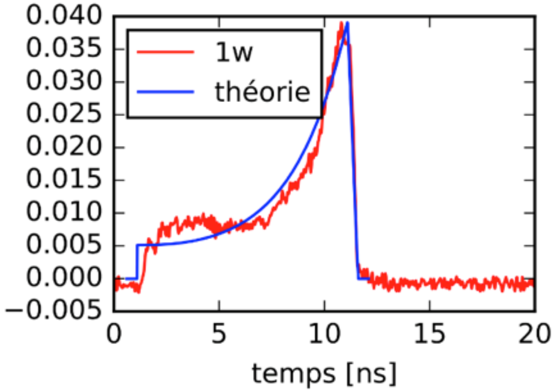

Chain output  on-shot energy = **720J ≈ 410+310 J**

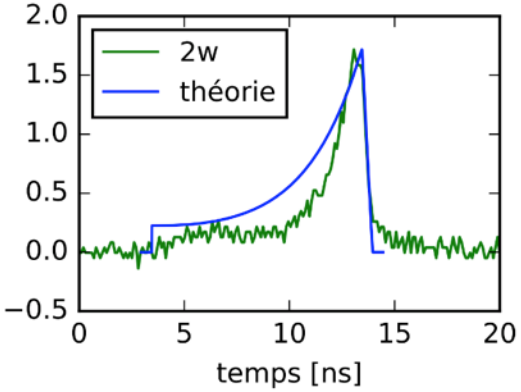
Long ns pulses up to **20 ns**




Ouput profile

**15 ns 503 J**



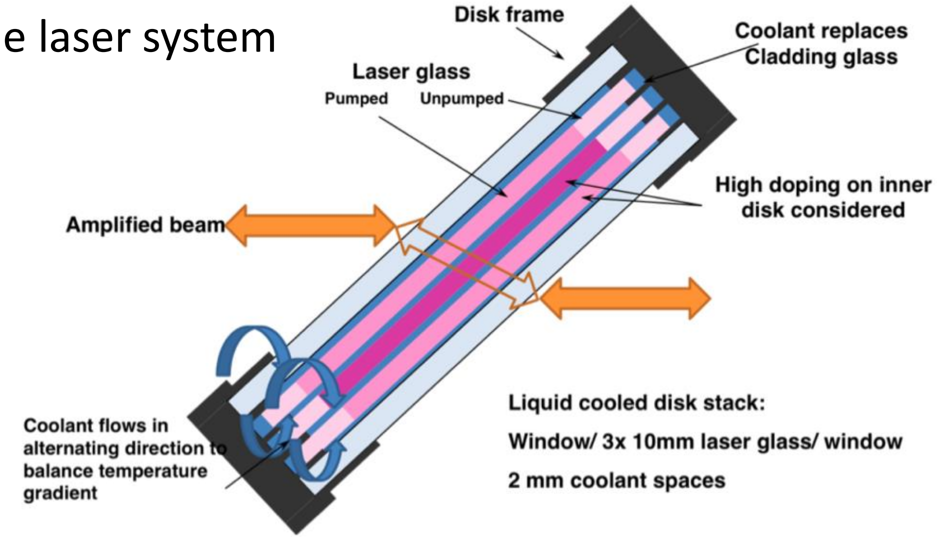

Main difficultys :

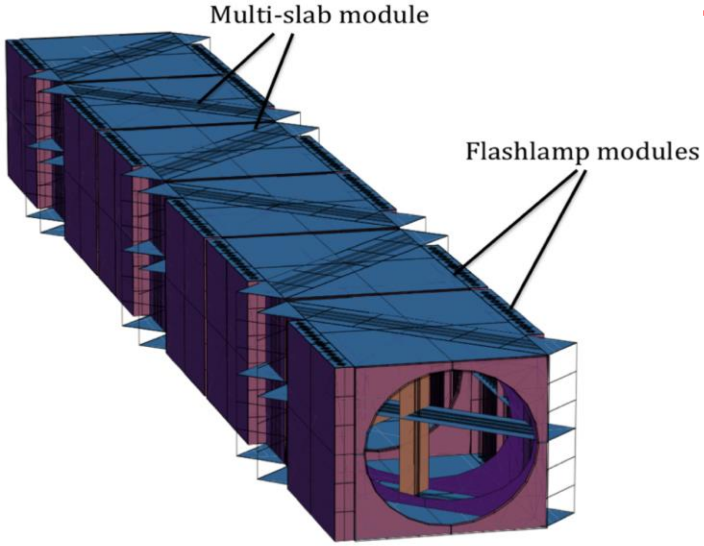
- gain pre-compensation
- SHG efficiency
- Transverse Brillouin Scattering

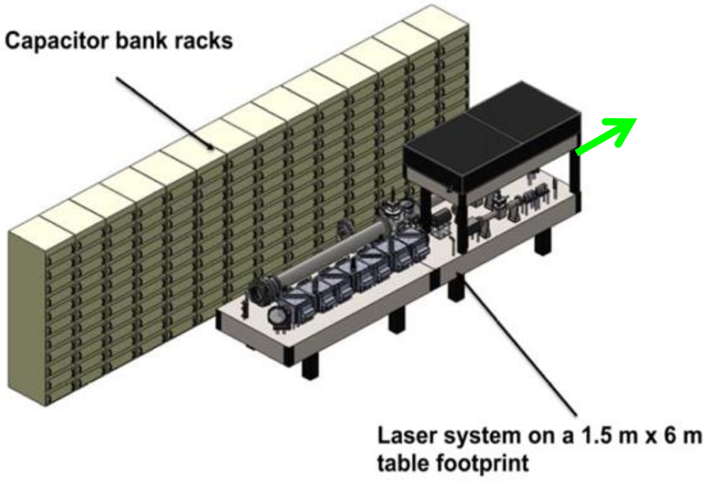
# Laser development

## CNE 400 LASER

- Amplitude laser system




### Main characteristics of 1st module

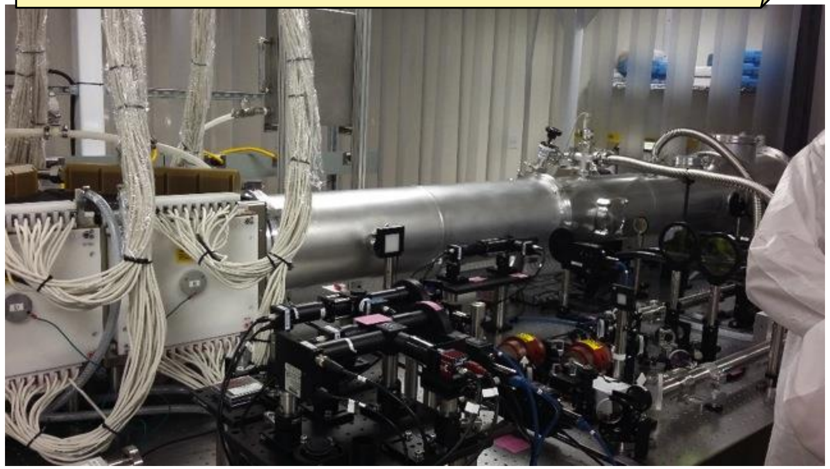
| | |
|---|---|
| Energy per pulse, $E_0$ | 200 J **at 527 nm** |
| Rep rate | $T_{rep}$ = **1 shot/min** |
| Temporal specifications | Rectangular :<br>$\Delta t$ = 30 +/- 10 ns |
| Beam shape | Circular |
| Dimensions | < to 6 m x 1.5 m x 2 m |

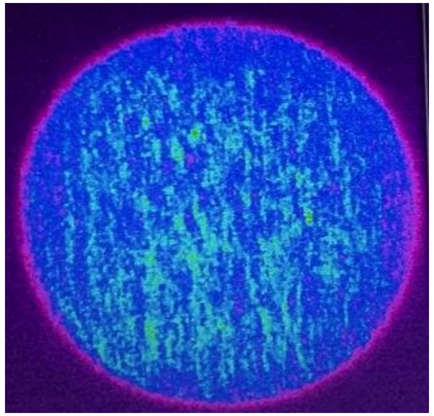
design by Continuum & National Energetics

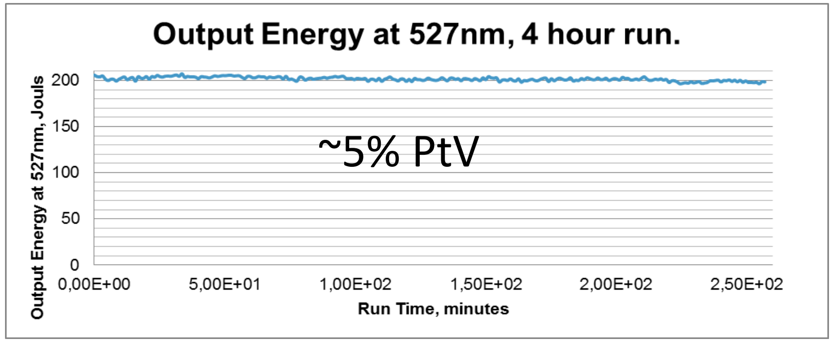
# High energy 200J/mn @527 nm glass laser: CNE400

200 Joules (527nm)

Delivery in France: **09/2016**
Under reception








- ✓ Novel liquid cooled multi-slab technology
- ✓ **200 Joules/min** at 527 nm / Uniform beam
- ✓ Reliable / turn-key operation
- ✓ Pulse shaping 30ns square

# Targets for high repetition rate facilities

- One beam operation
  - High repetition rate targets can be used
    - – Target wheels, target mounted on frames, etc.
    - – Continuous target system
  - – Well define alignment procedure needed
- Multiple beam operation
  - complex target arrangement
    - Shot rate will be low
  - Using a target loader with a stack of 10 targets, can still get 20-30 shots/hour ~ 150 targets/day

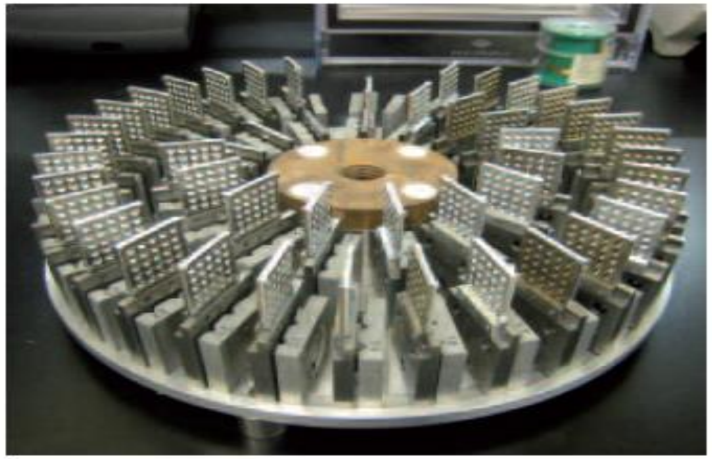
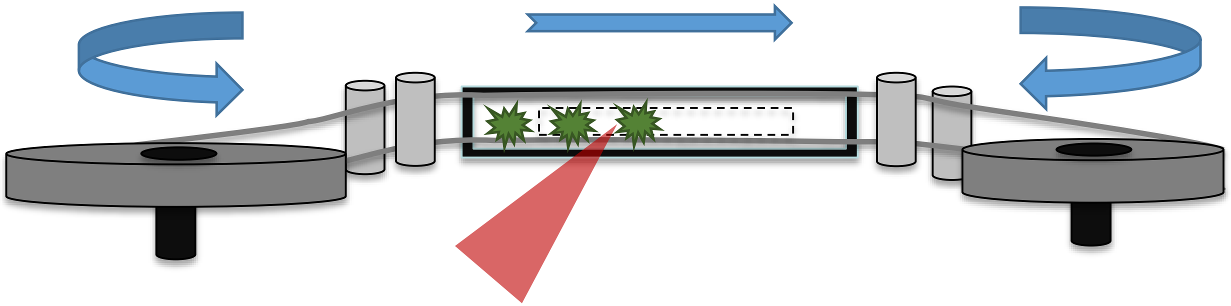
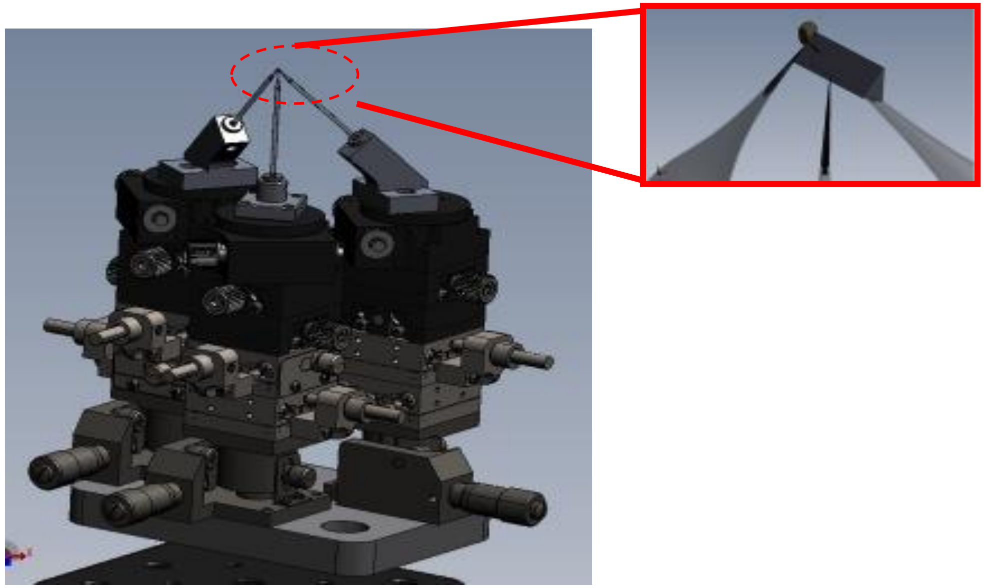


Figure 1a. Inserter carousel populated with 5×5 foil array.





# Conclusions

- X-ray sources coupled with high energy optical laser will open new opportunities: To study matter under extreme condition with X-ray diagnostics techniques  allowing to access to microscopic structure.
  - Increase statistics
  - Broad the users community
- Need a reliable high energy laser
  - With pulse shaping and spatial uniformity
  - With good shock diagnostics  ( visar SOP…)
- Need to design experiment and develop technics to take advantage of the repetition rate at an affordable price