Core Mineral Physics

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Géodynamo

ISTerre

UNIVERSITÉ Grenoble Alpes

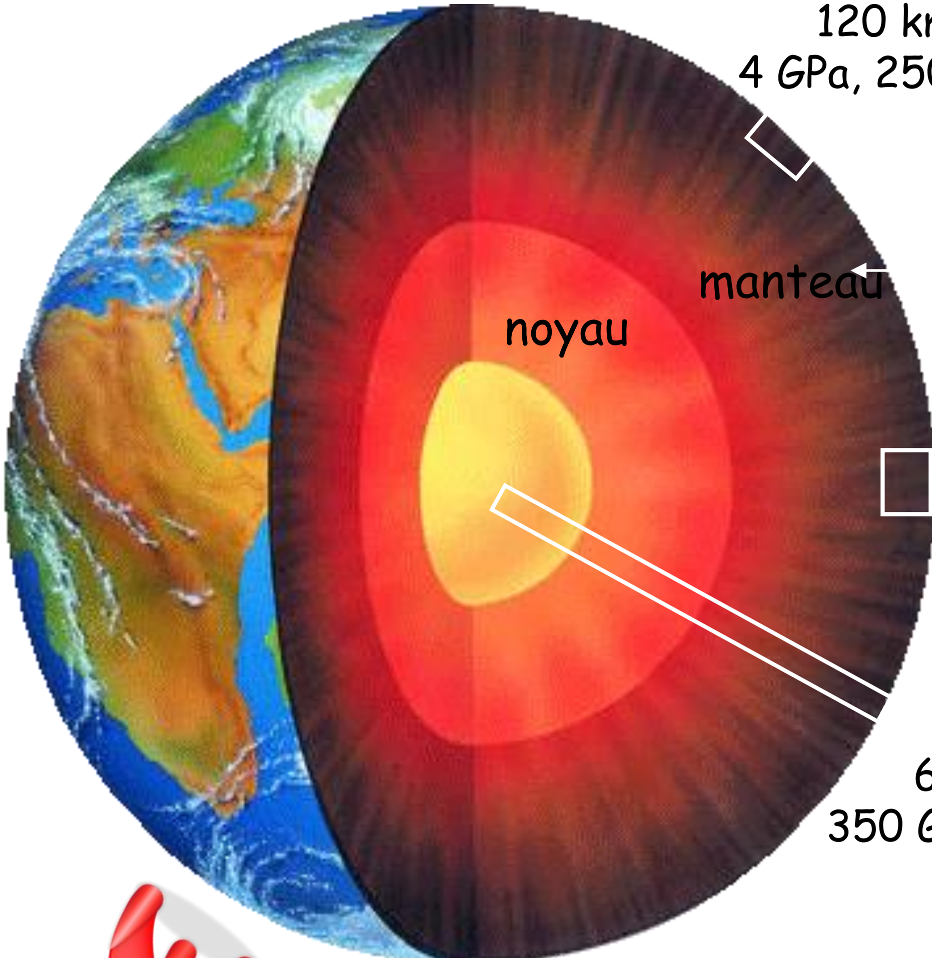
cnrs advancing the frontiers

Plan of the lesson

-Compressing stuff

-Then think …

Experiments HP-HT



120 km
4 GPa, 2500 °C

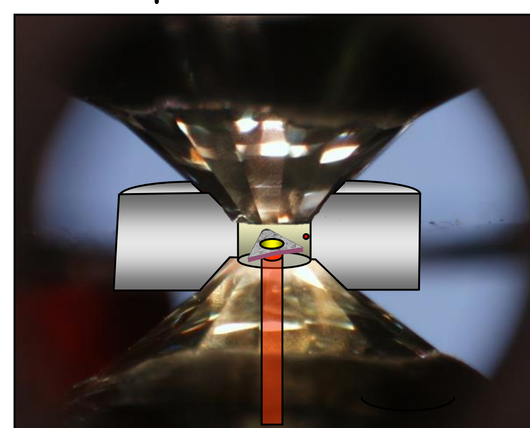
750 km
25 GPa, 2700 °C

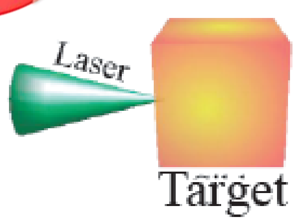
6300 km
350 GPa, 6000 °C

5 mm

0.5 mm

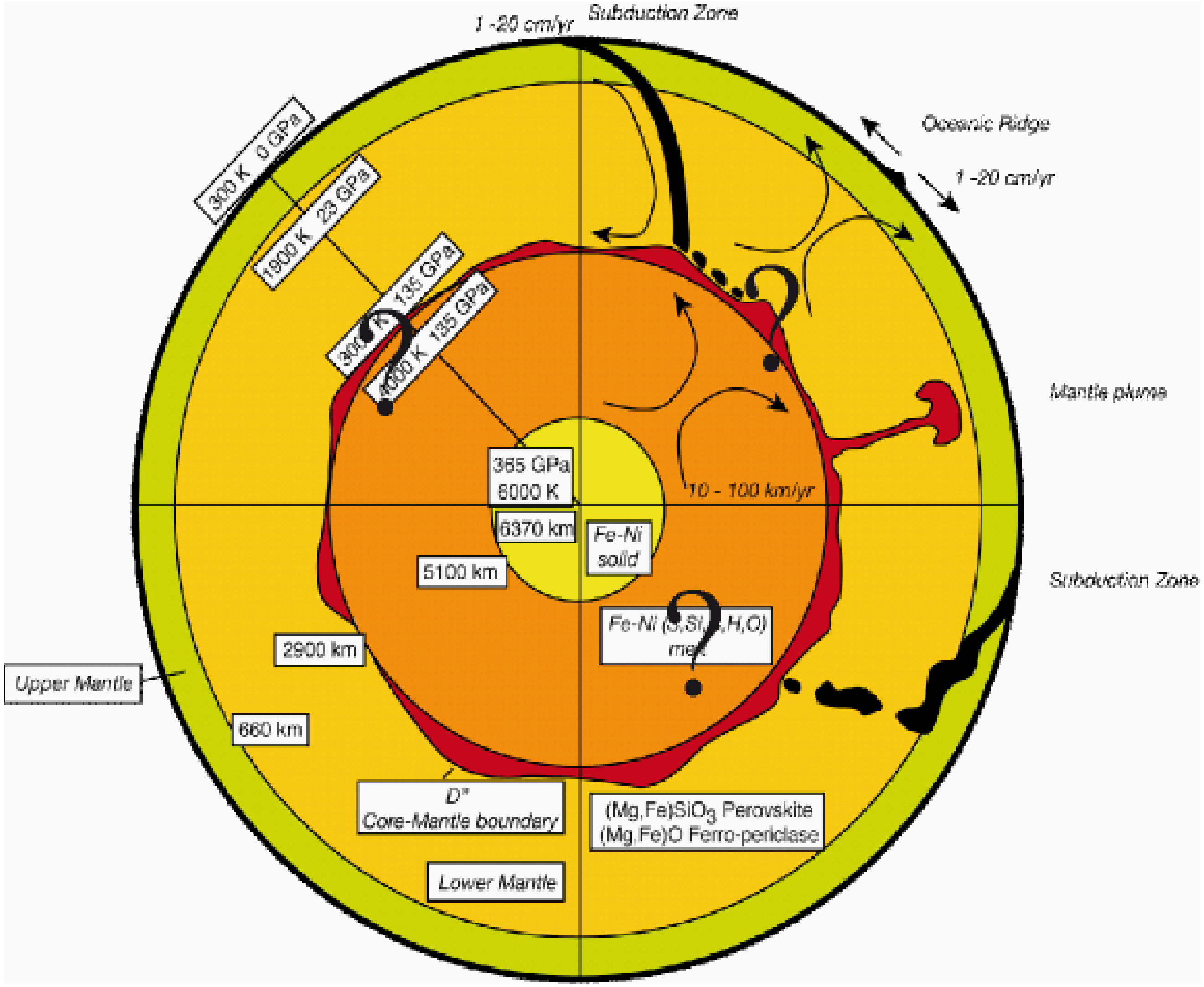
5-20 µm

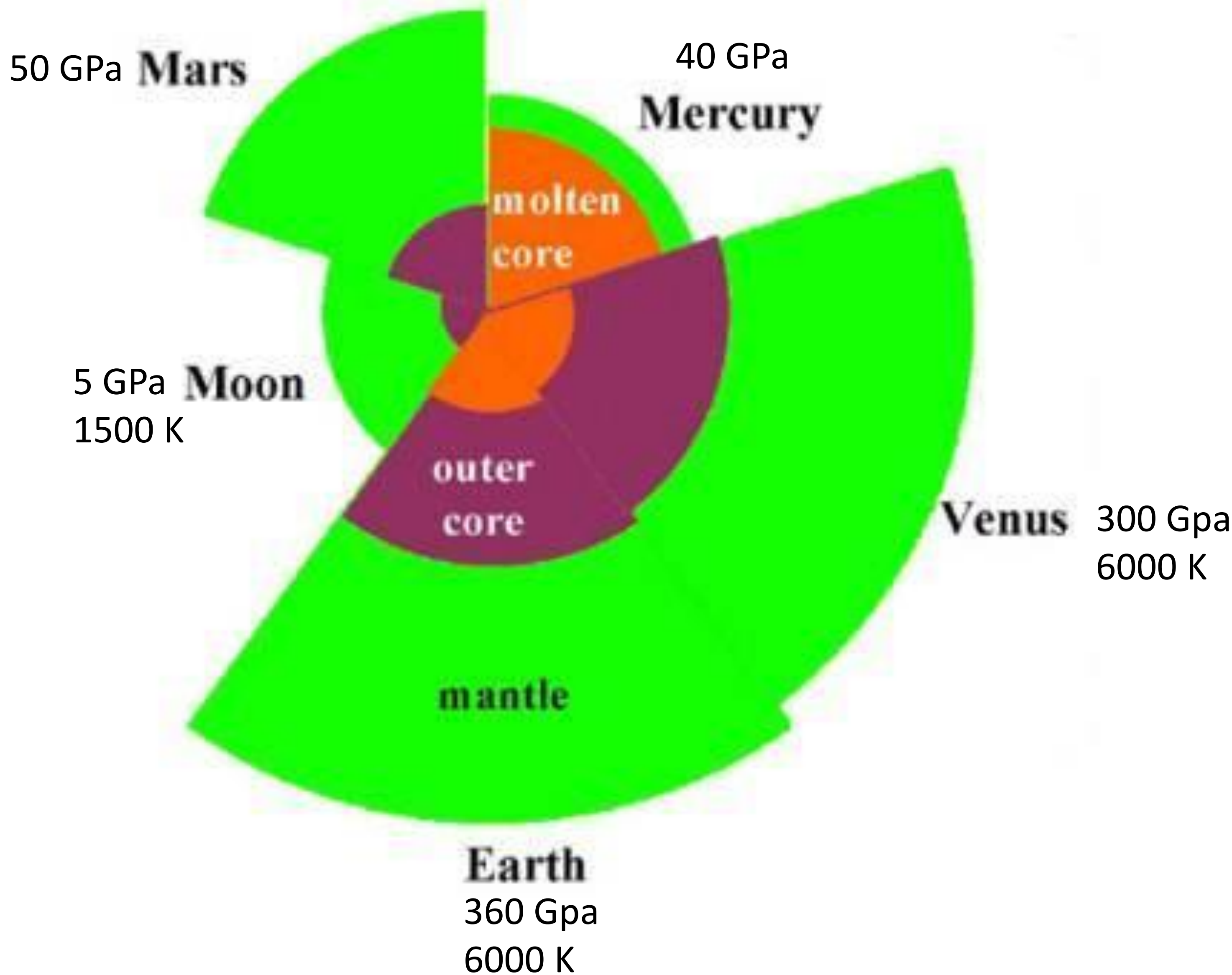


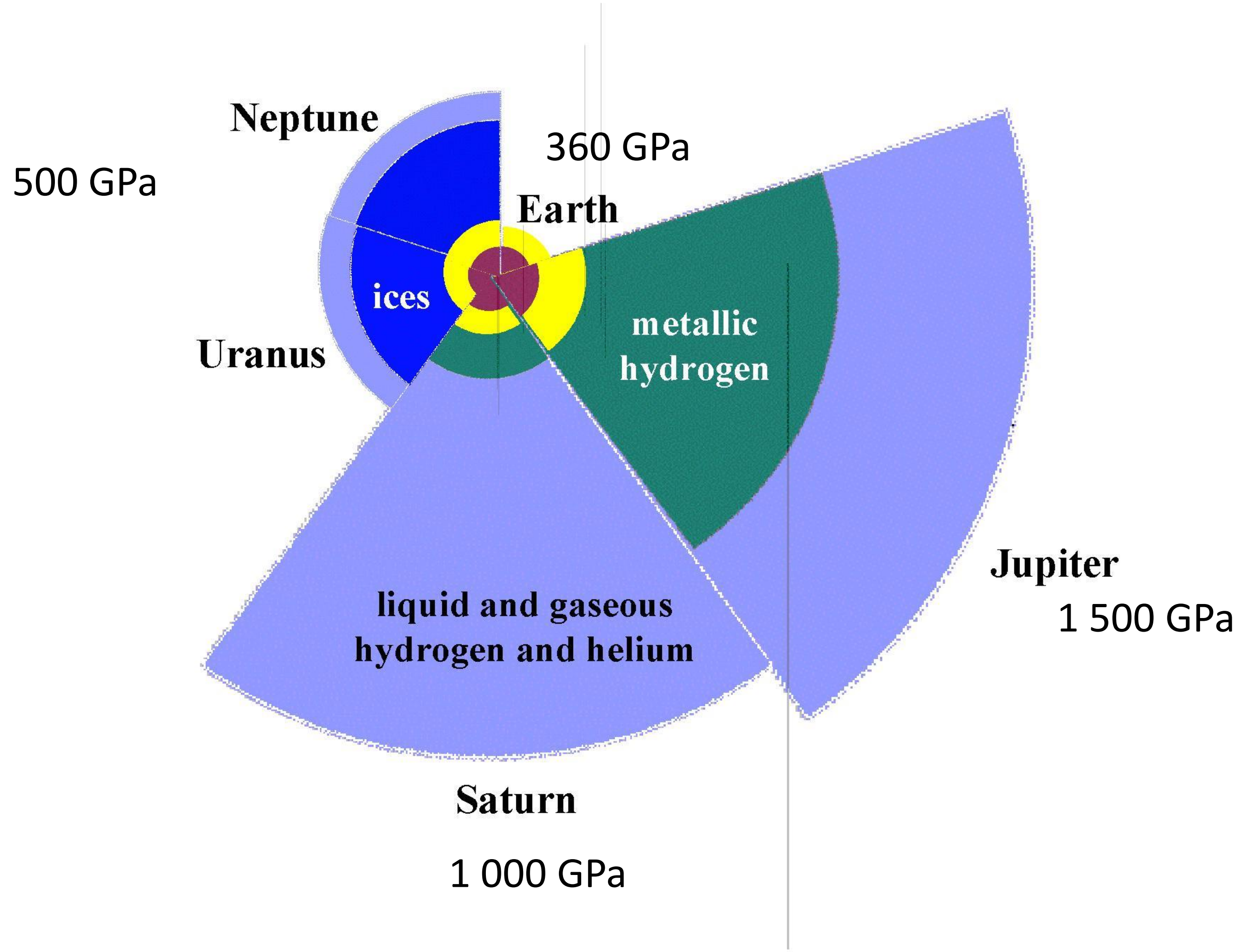


Intérieur des exoplanètes
1 TPa, T>10 000 °C
Mais sur 1-2 ns

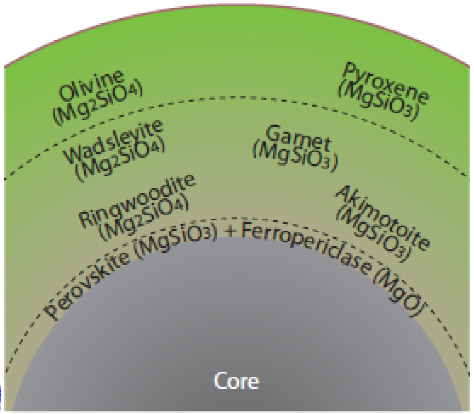
Internal structure of the Earth




50 GPa Mars
40 GPa
Mercury
molten core
5 GPa Moon
1500 K
outer core
Venus 300 Gpa
6000 K
mantle
Earth
360 Gpa
6000 K


Neptune
500 GPa
360 GPa
Earth
ices
Uranus
metallic
hydrogen
liquid and gaseous
hydrogen and helium
Jupiter
1 500 GPa
Saturn
1 000 GPa

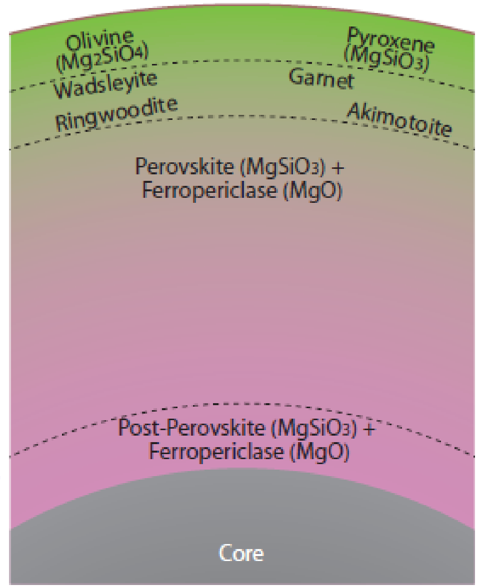
Mars



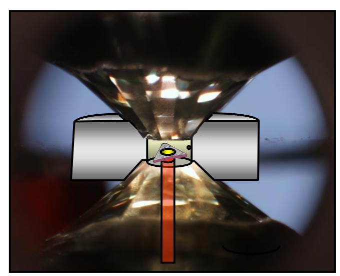
Presse multi-enclumes

~20 GPa

Earth

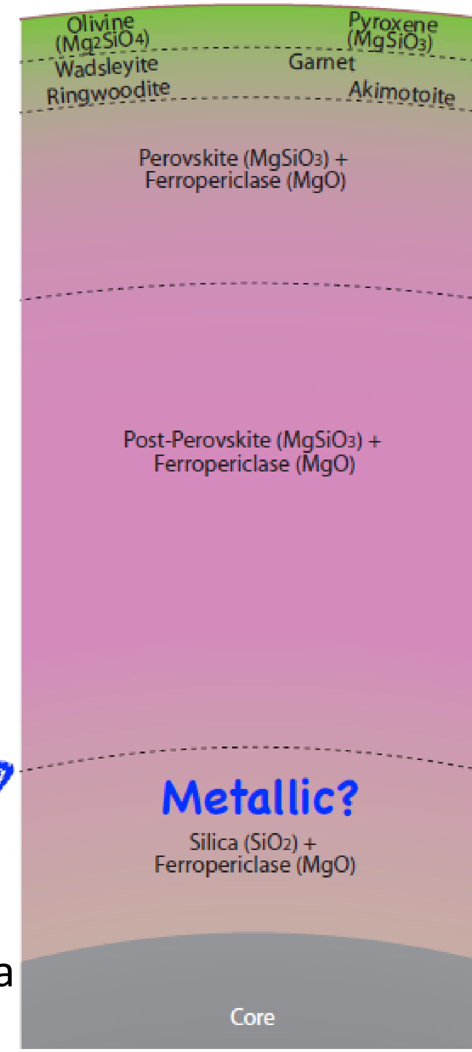


136 GPa



Cellule à enclumes de diamants

Super-Earth

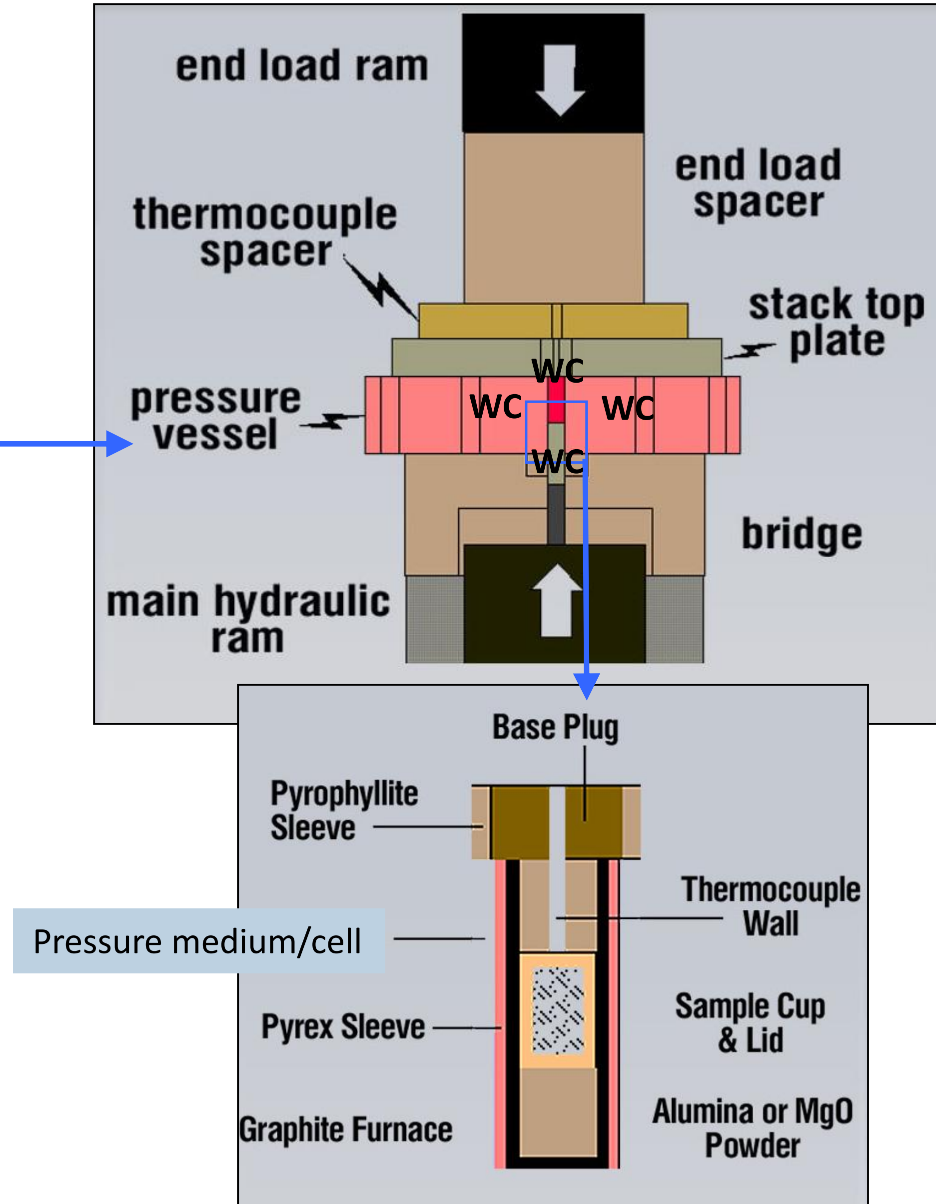


~1000 GPa

CHOCS !!!

After D.Shim

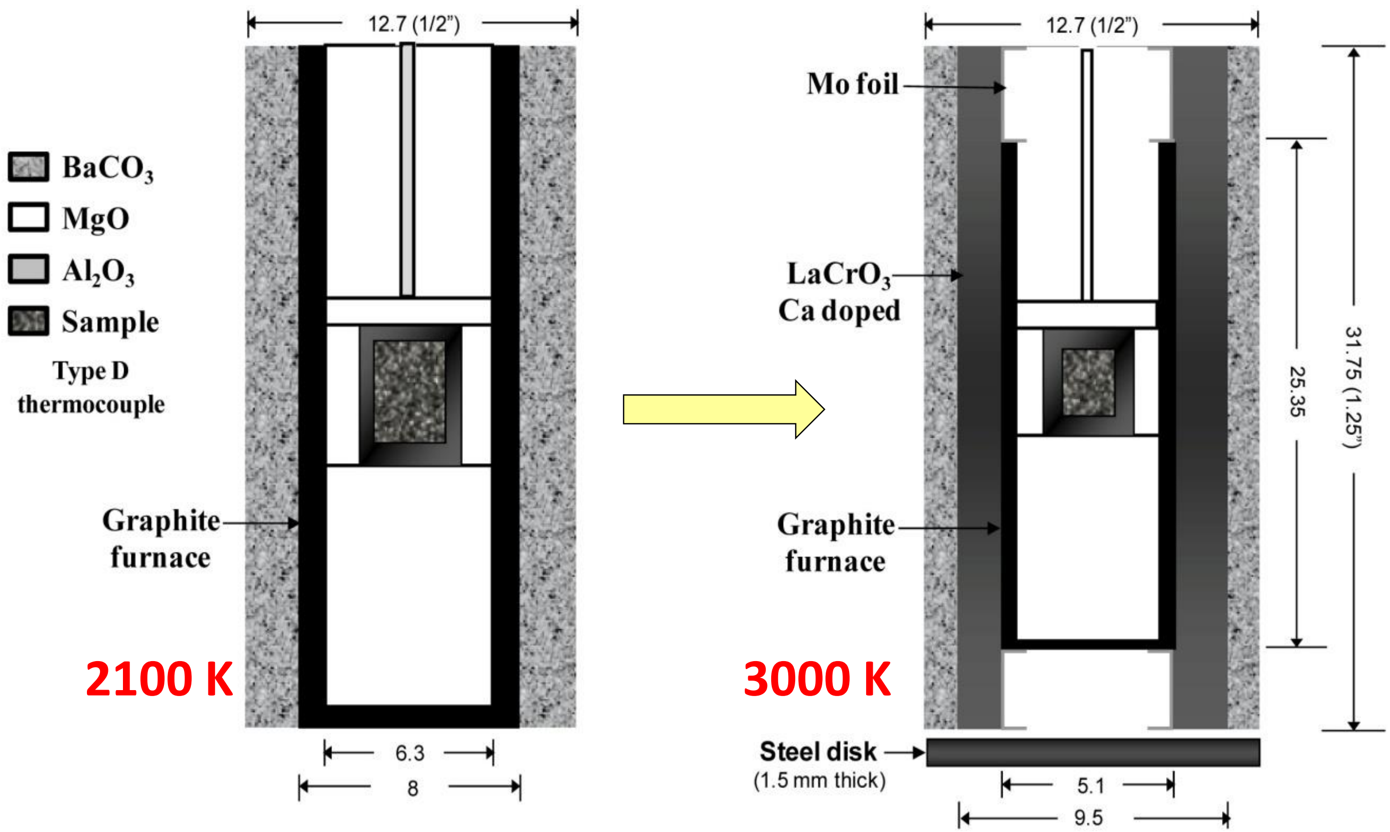
Hydraulic press - Piston cylinder

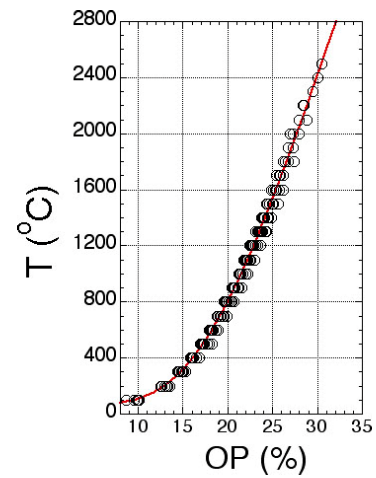


Pressure is directly derived from
The size of the piston Ø
BUT friction loss

Hydraulic press - Piston cylinder

High T assemblies





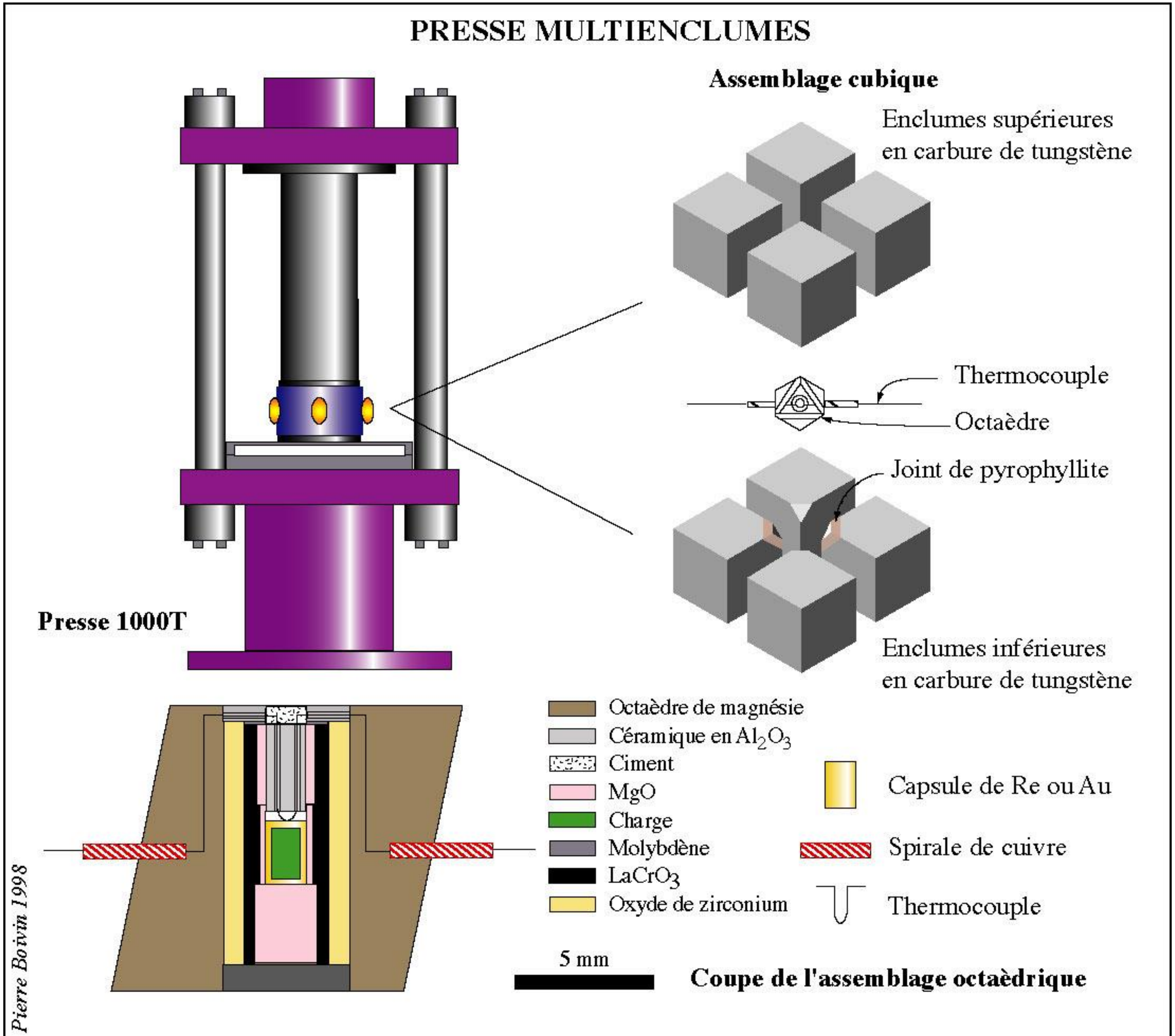
Resistive furnace

Temperature measured using thermocouple

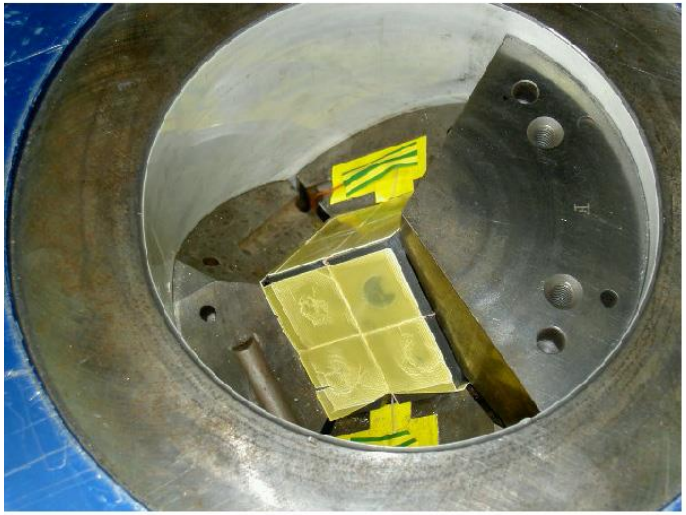
Hydraulic press – Multi-anvil press

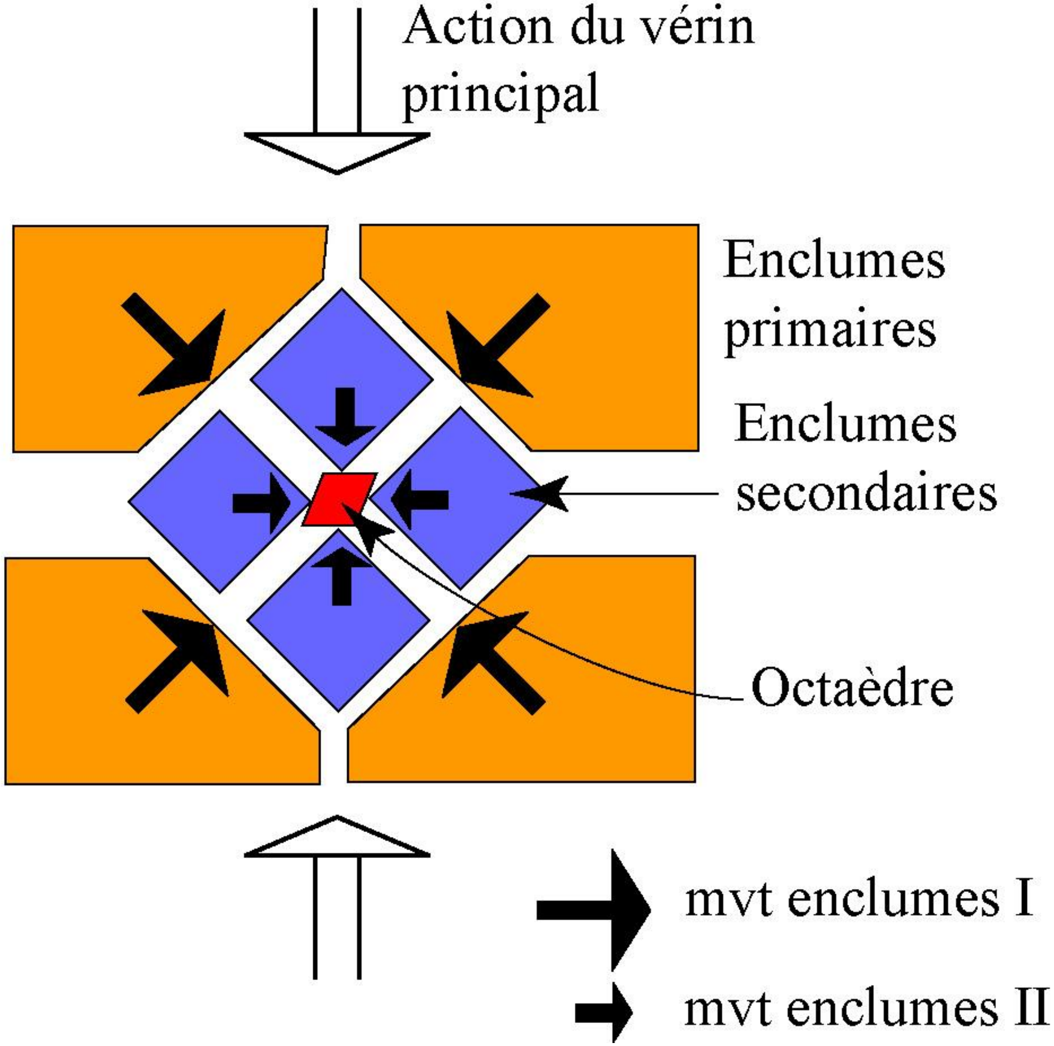
Working range

- Pressure : 3 - 26 GPa (carbides); 80-100 GPa (sintered diamonds)
- Temperature : RT to 2500°C
- Duration : several days at T<1600°C


PRESSE MULTIENCLUMES
Assemblage cubique
Enclumes supérieures en carbure de tungstène
Thermocouple
Octaèdre
Joint de pyrophyllite
Enclumes inférieures en carbure de tungstène
Presse 1000T
Octaèdre de magnésie
Céramique en Al_2O_3
Ciment
MgO
Charge
Molybdène
$LaCrO_3$
Oxyde de zirconium
Capsule de Re ou Au
Spirale de cuivre
Thermocouple
5 mm
Coupe de l'assemblage octaèdrique
Pierre Boivin 1998

Forces

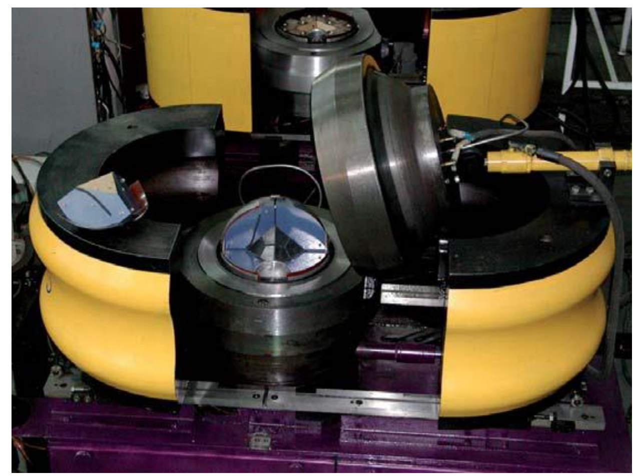



Action du vérin principal
Enclumes primaires
Enclumes secondaires
Octaèdre
mvt enclumes I
mvt enclumes II

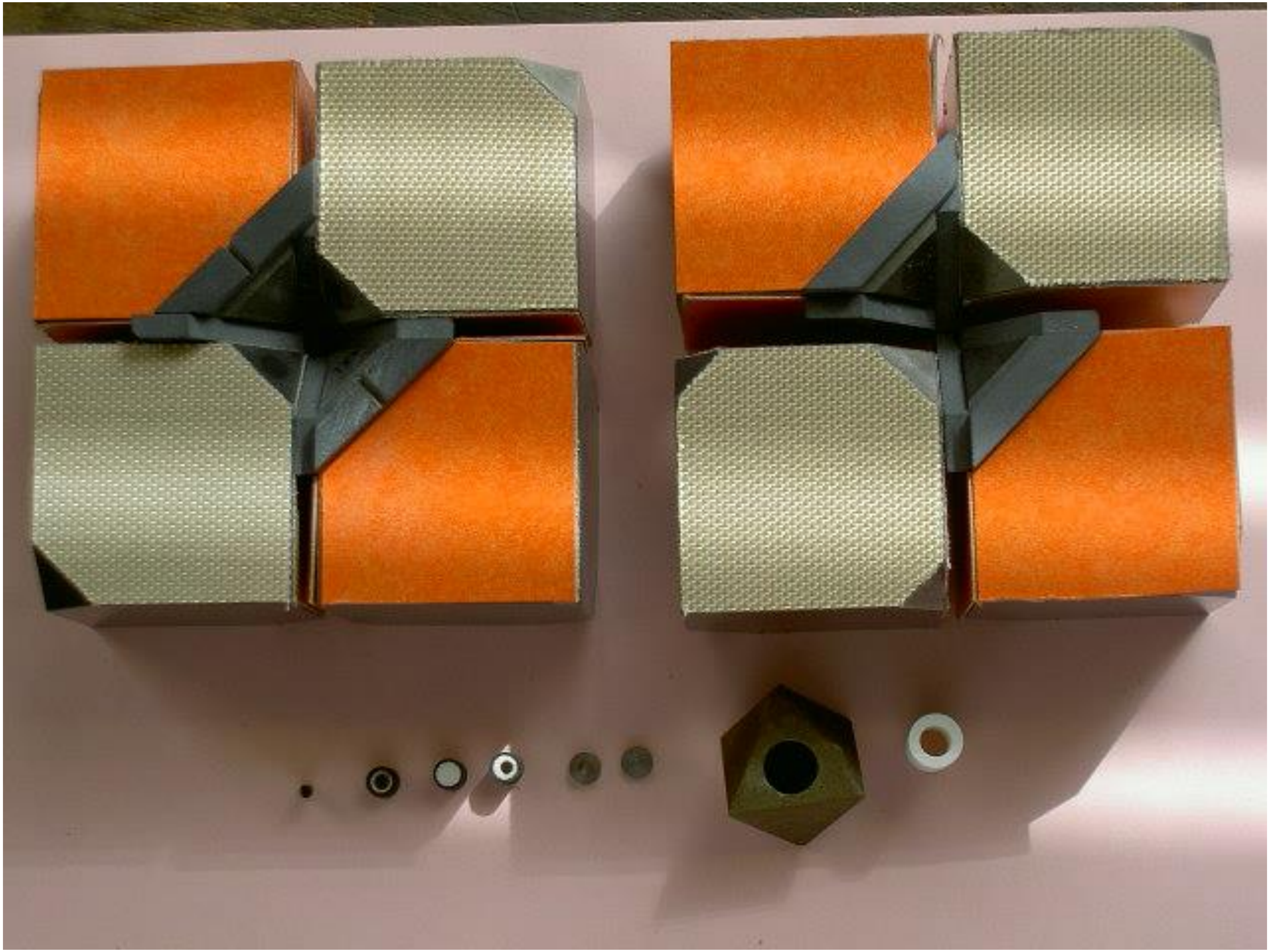
Press 1500 tons, Clermont Ferrand

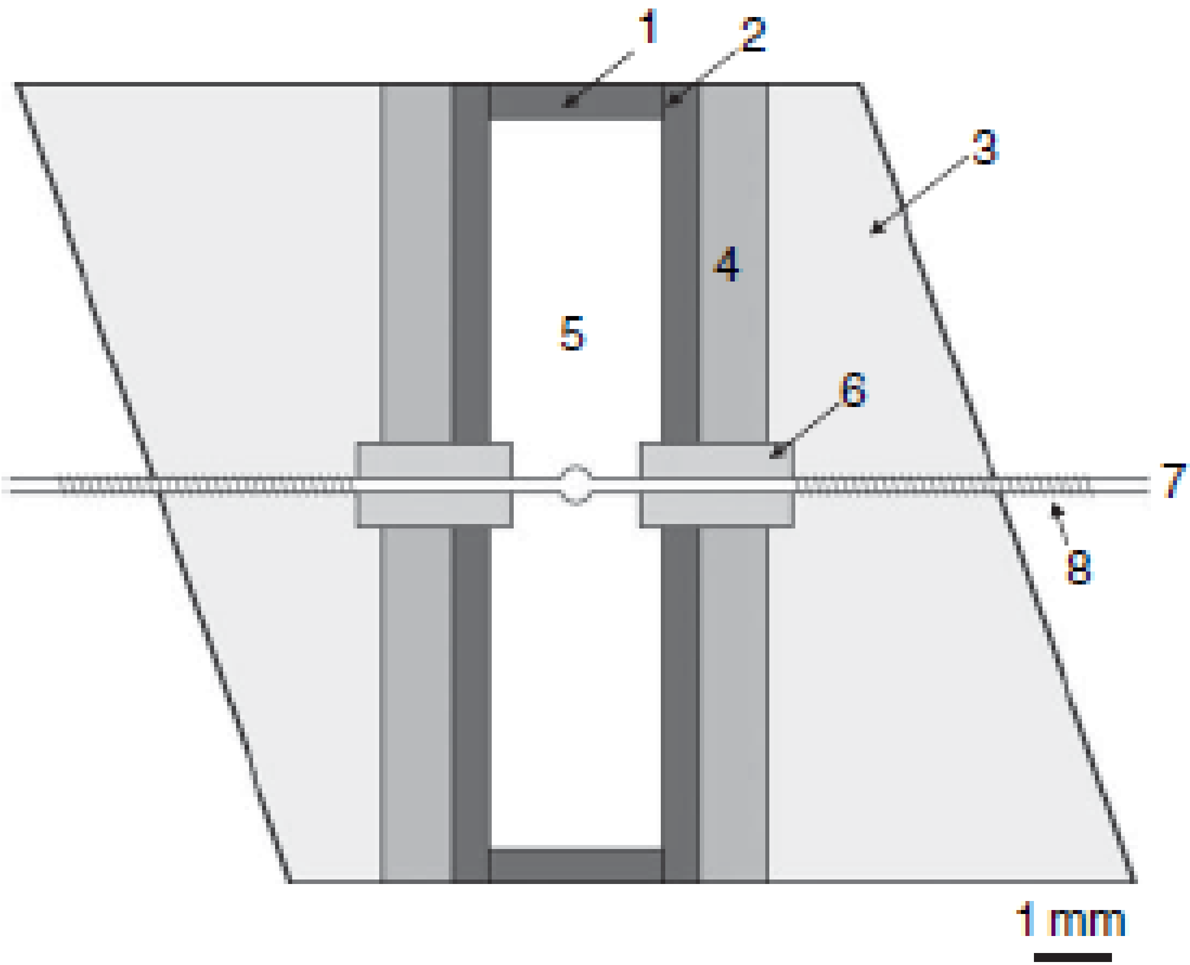
Press 5000 tons, Misasa, Japon

Press 6000 tons, Ehime, Japon

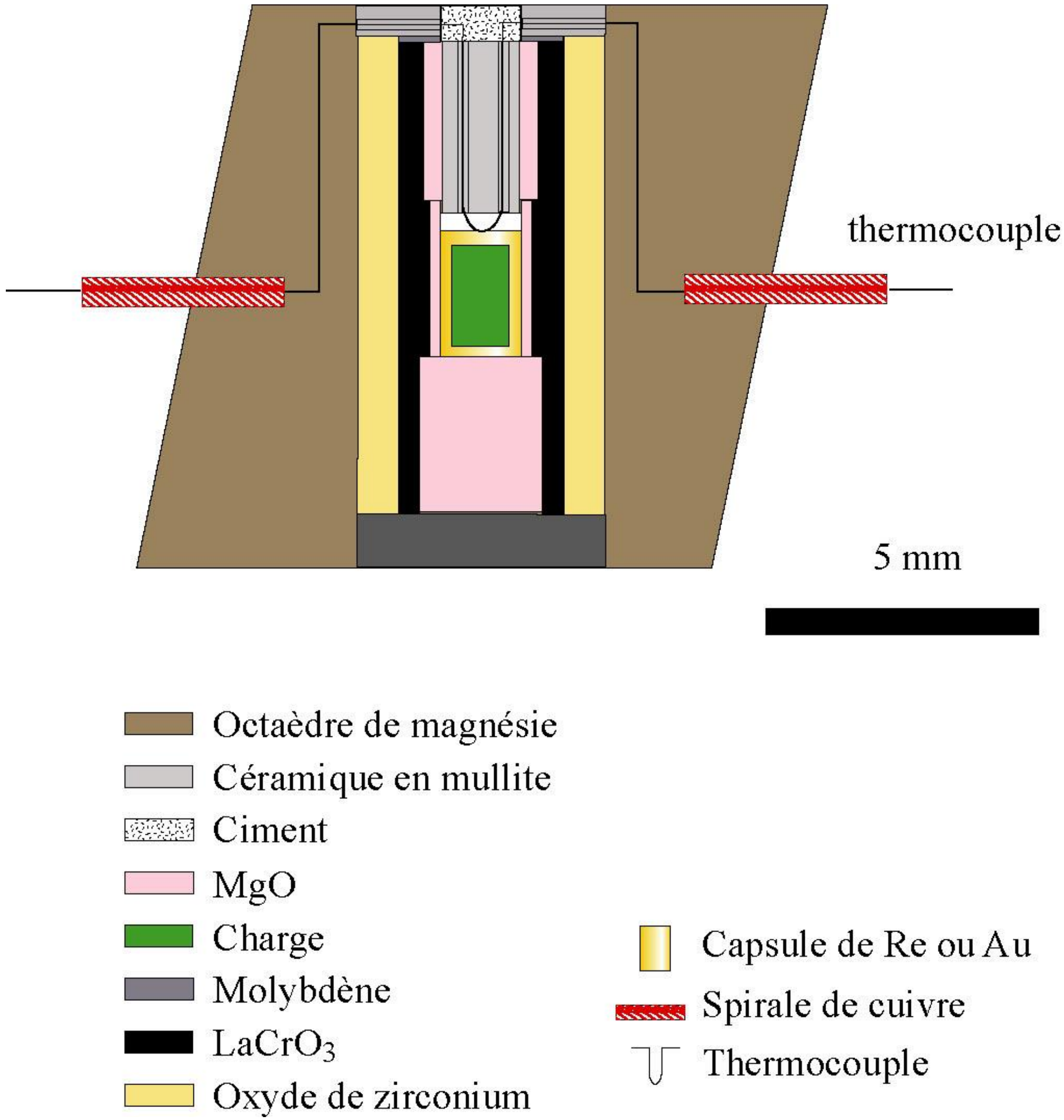


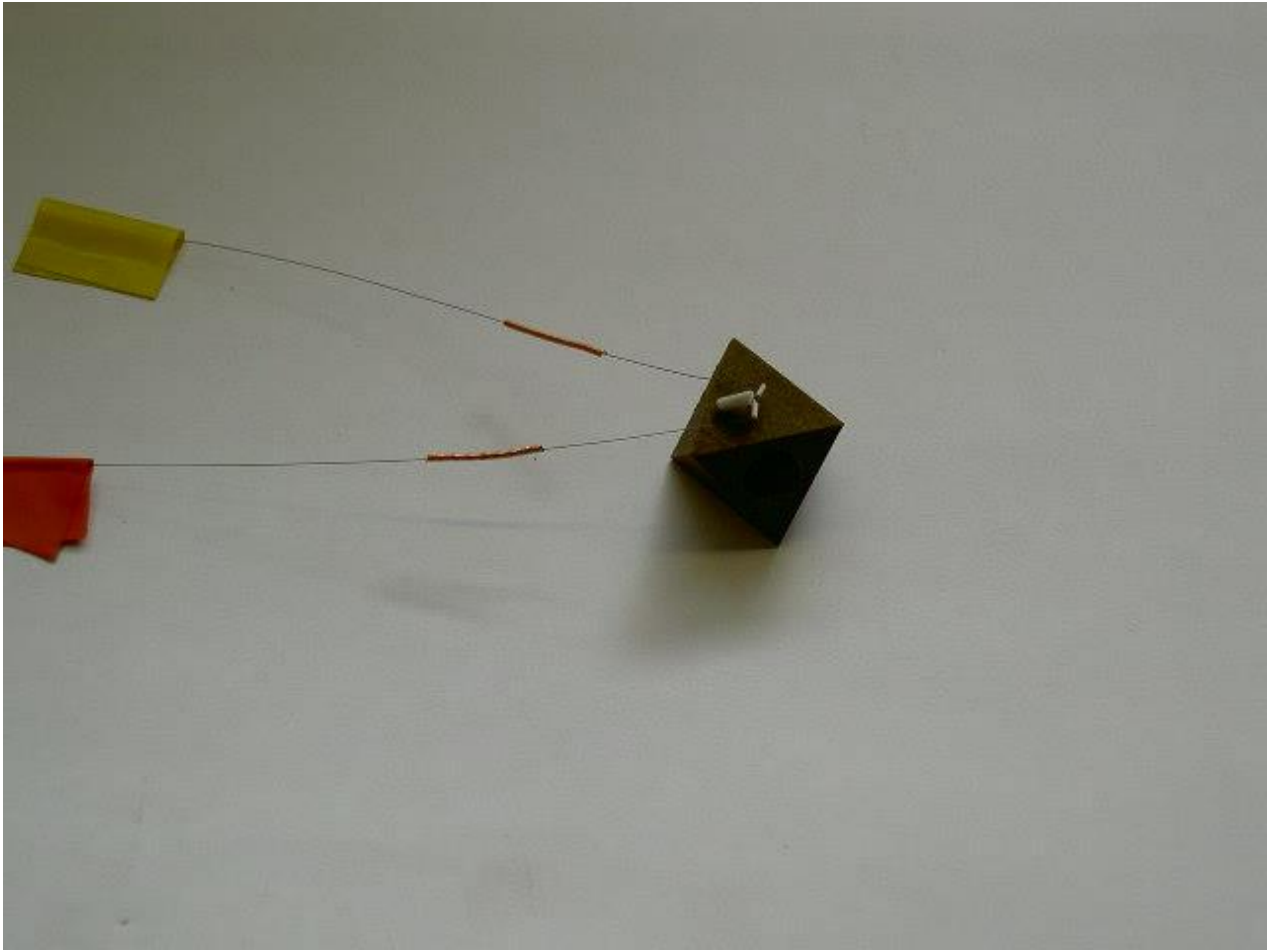
Press BARS, Novossibirsk, Russie

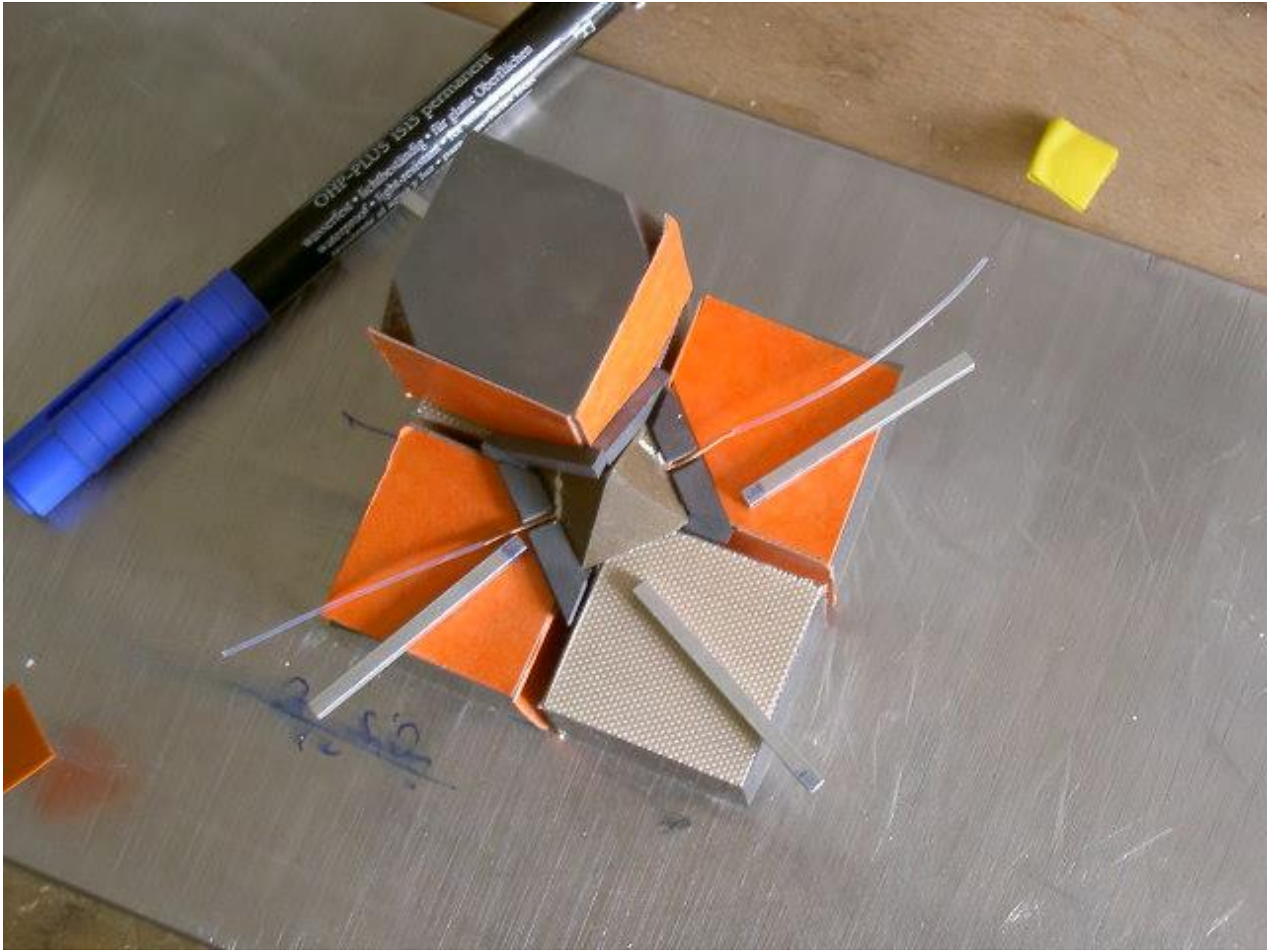


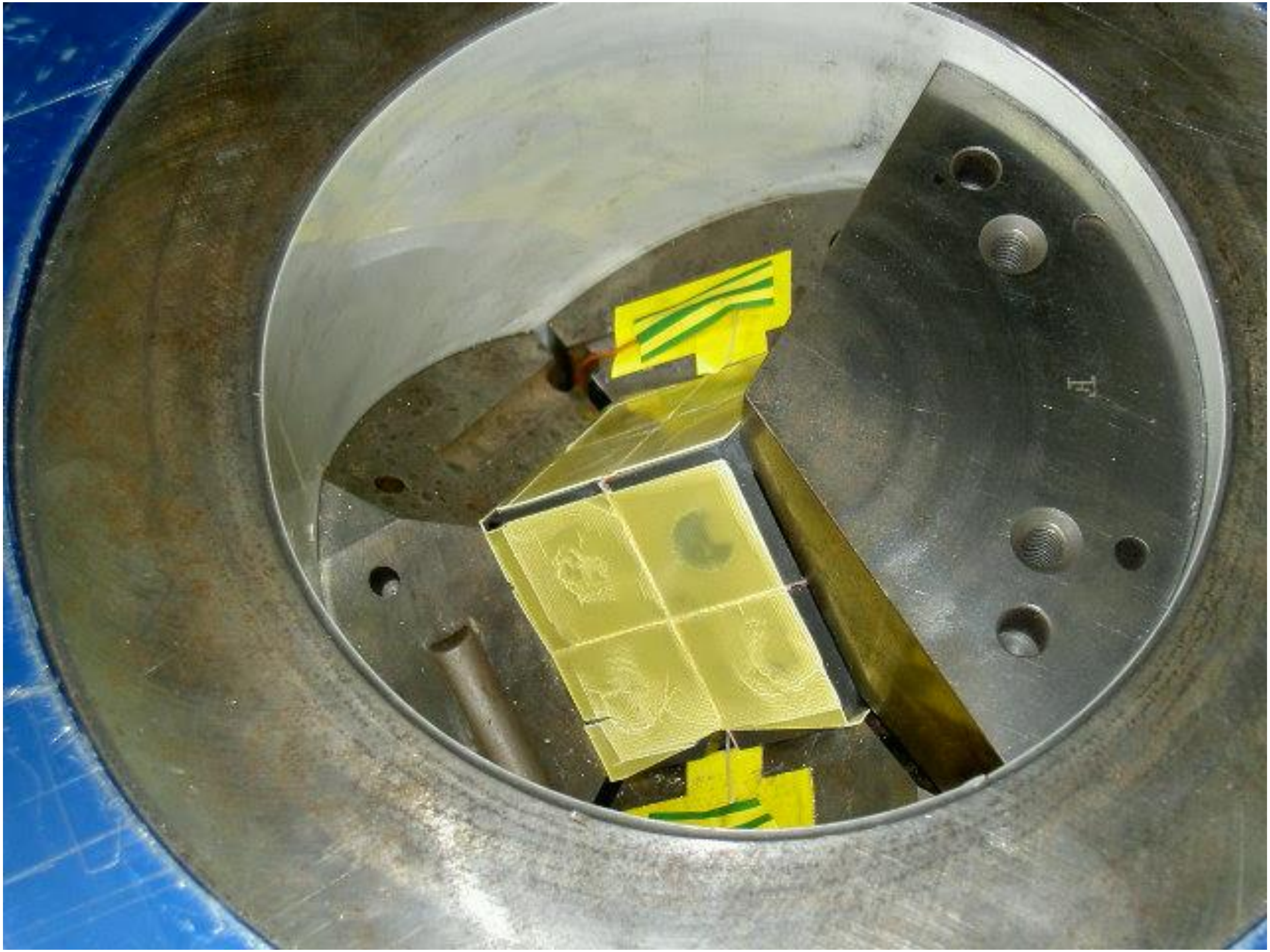


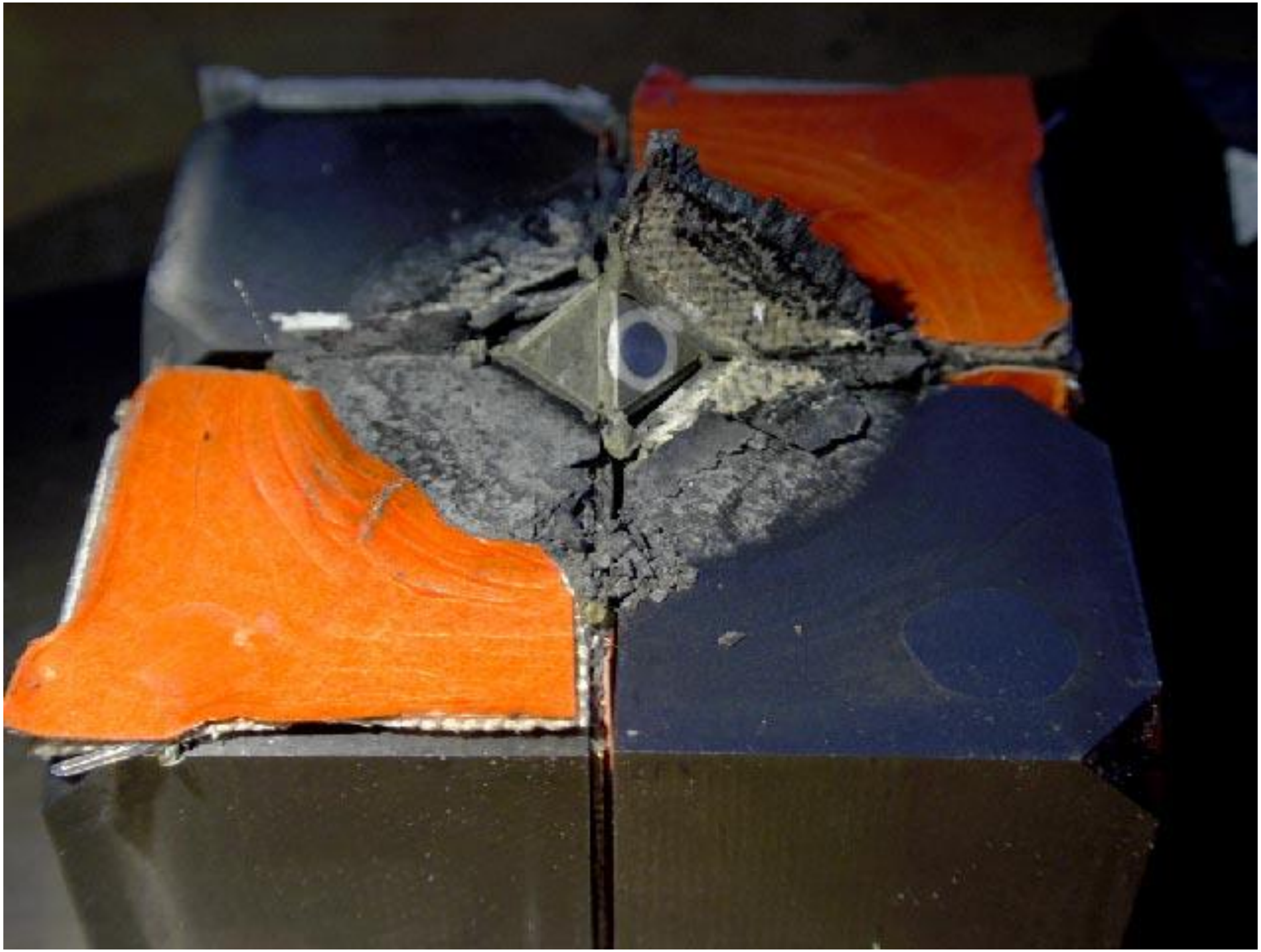
1: Lid; 2: Heater; 3: Pressure medium;
4: Thermal insulator; 5: Sample;
6: Electric insulator; 7: Thermocouple;
8: Coil


thermocouple
5 mm
Octaèdre de magnésie
Céramique en mullite
Ciment
MgO
Charge
Molybdène
$LaCrO_3$
Oxyde de zirconium
Capsule de Re ou Au
Spirale de cuivre
Thermocouple

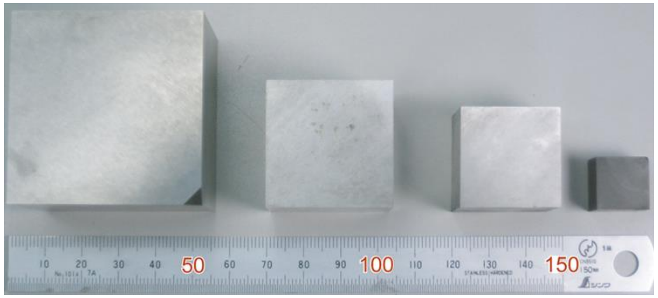


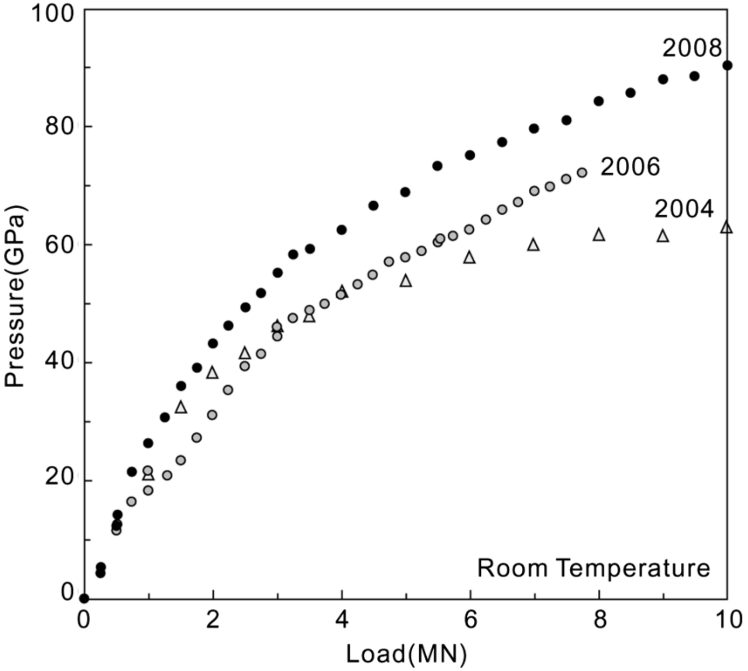

OHP-PLUS 1513 permanent

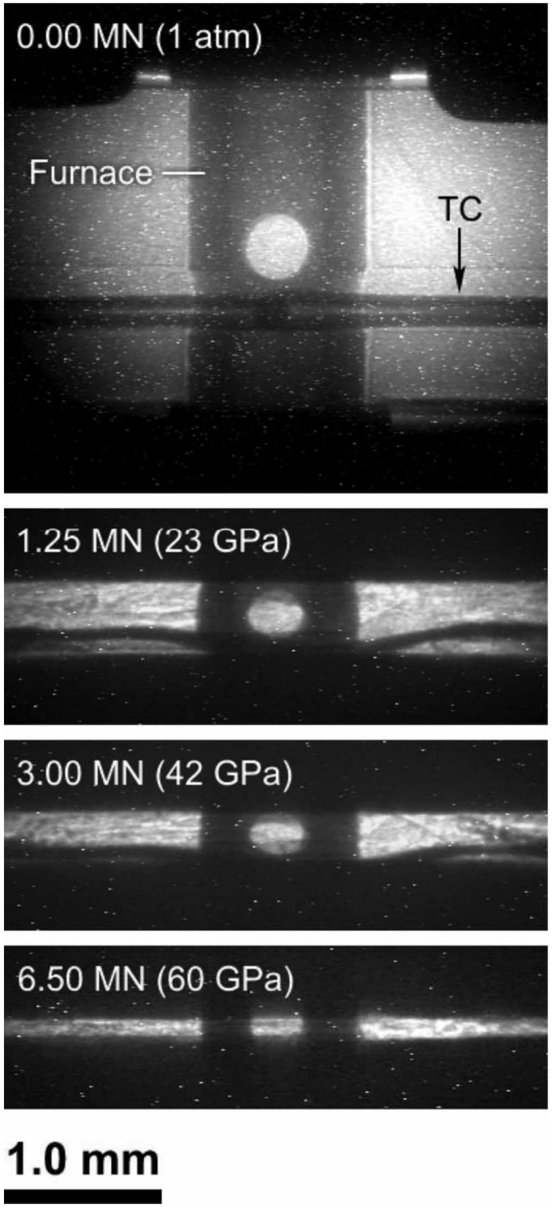




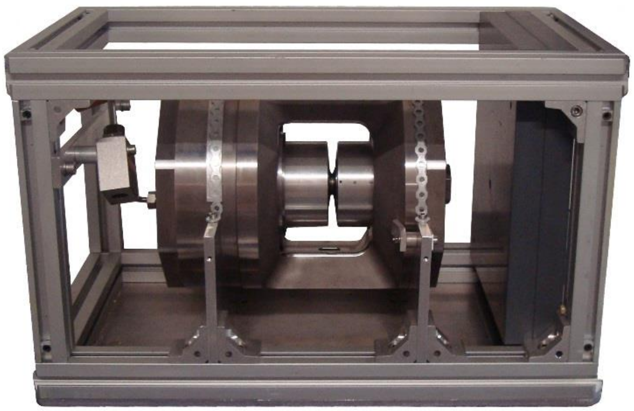
Sintered diamond anvils

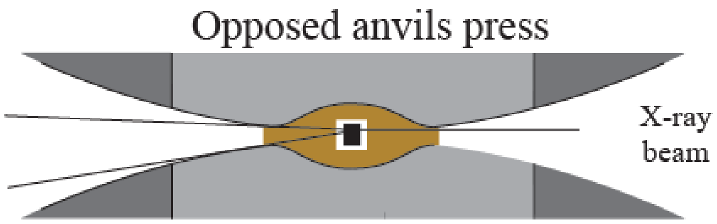




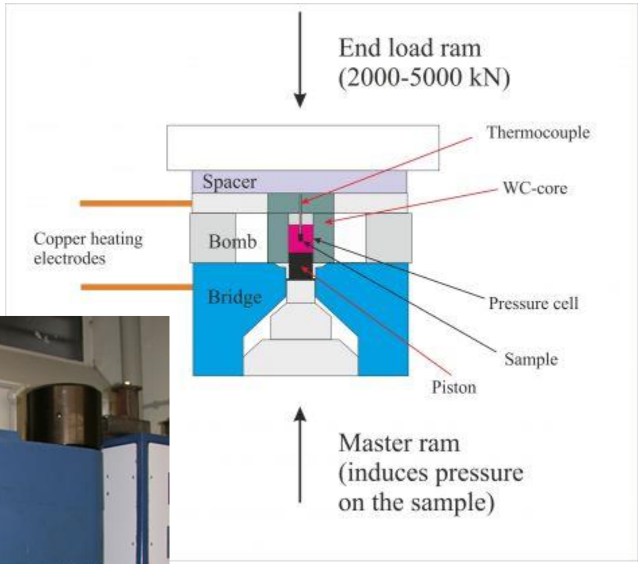


Other large volume presses





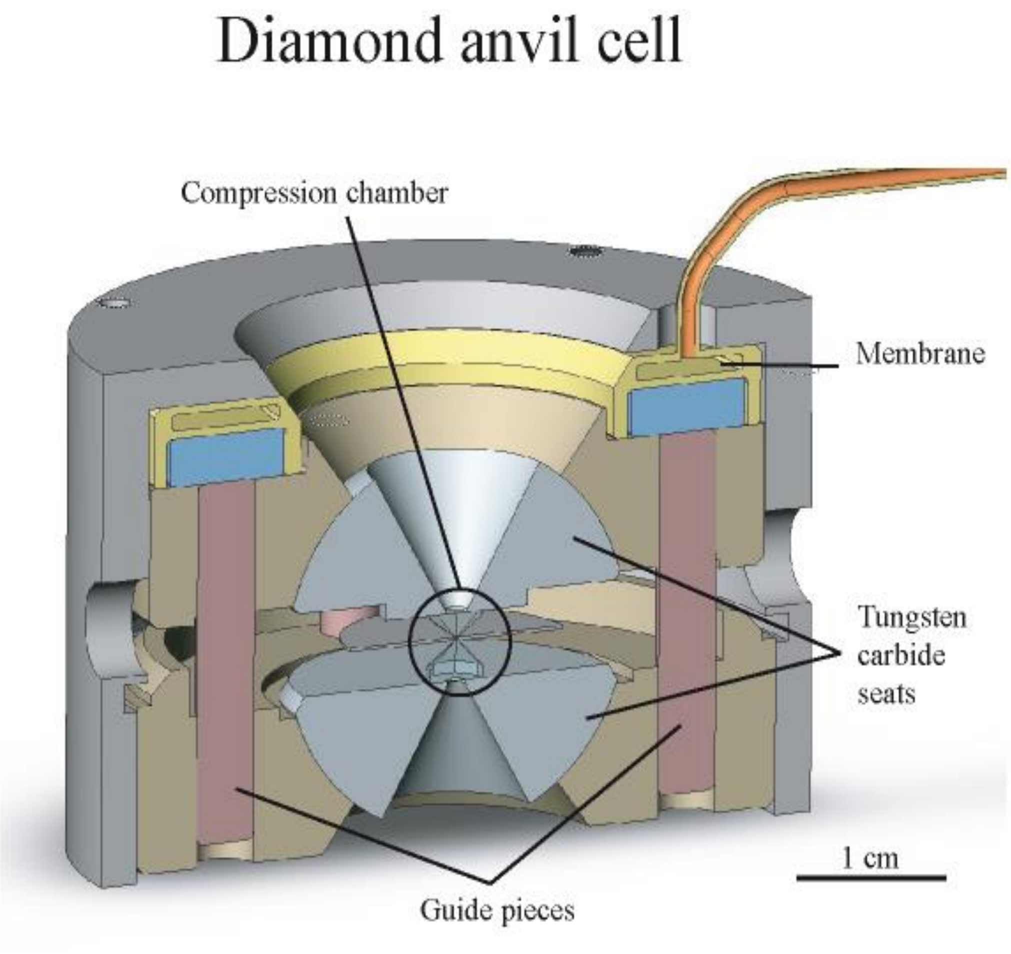
Paris-Edinburgh Press
Developped for in-situ experiments
Pressure up to ~15 Gpa
Temperature up to 2300 K



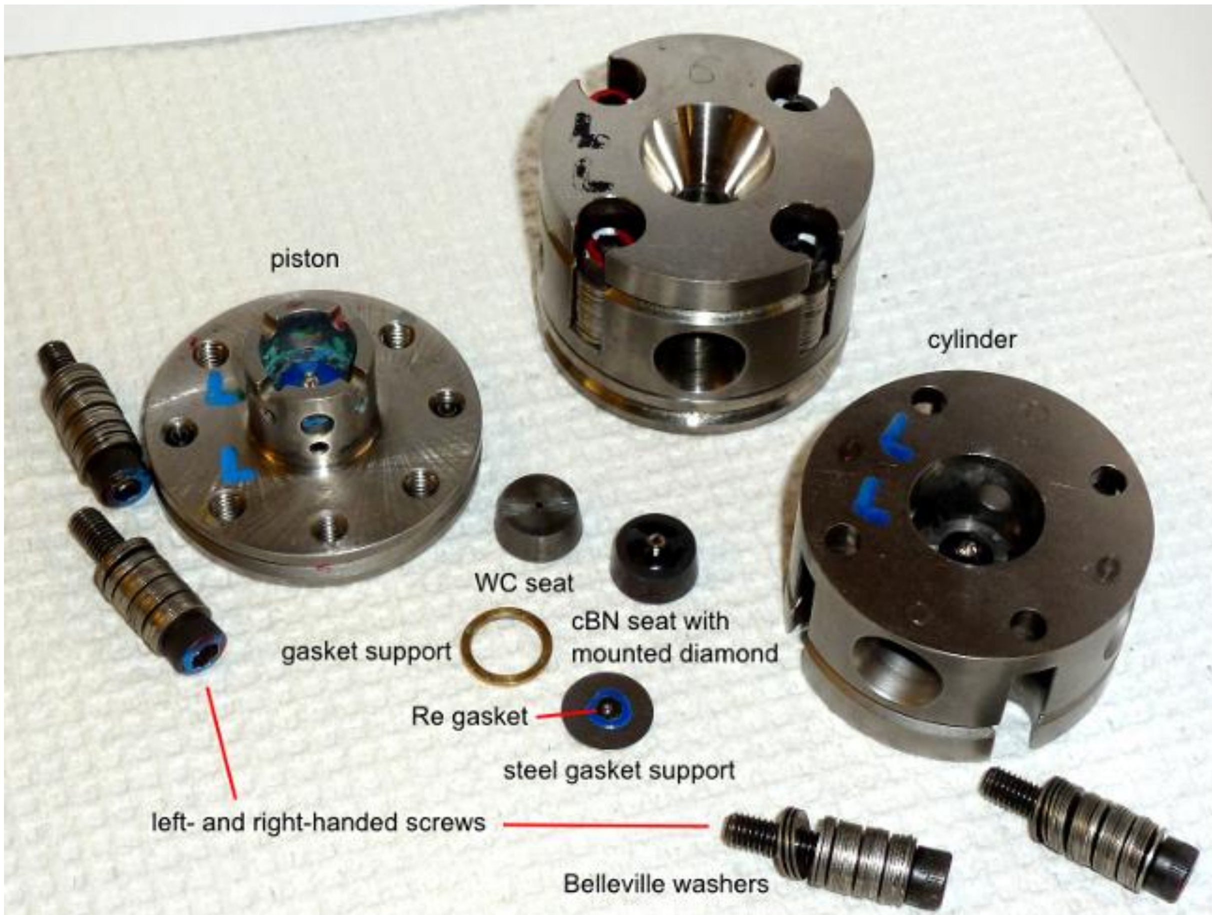
Piston cylinder apparatus
For ex situ synthesis
Pressure up to 4 Gpa
Temperature up to 2500 K

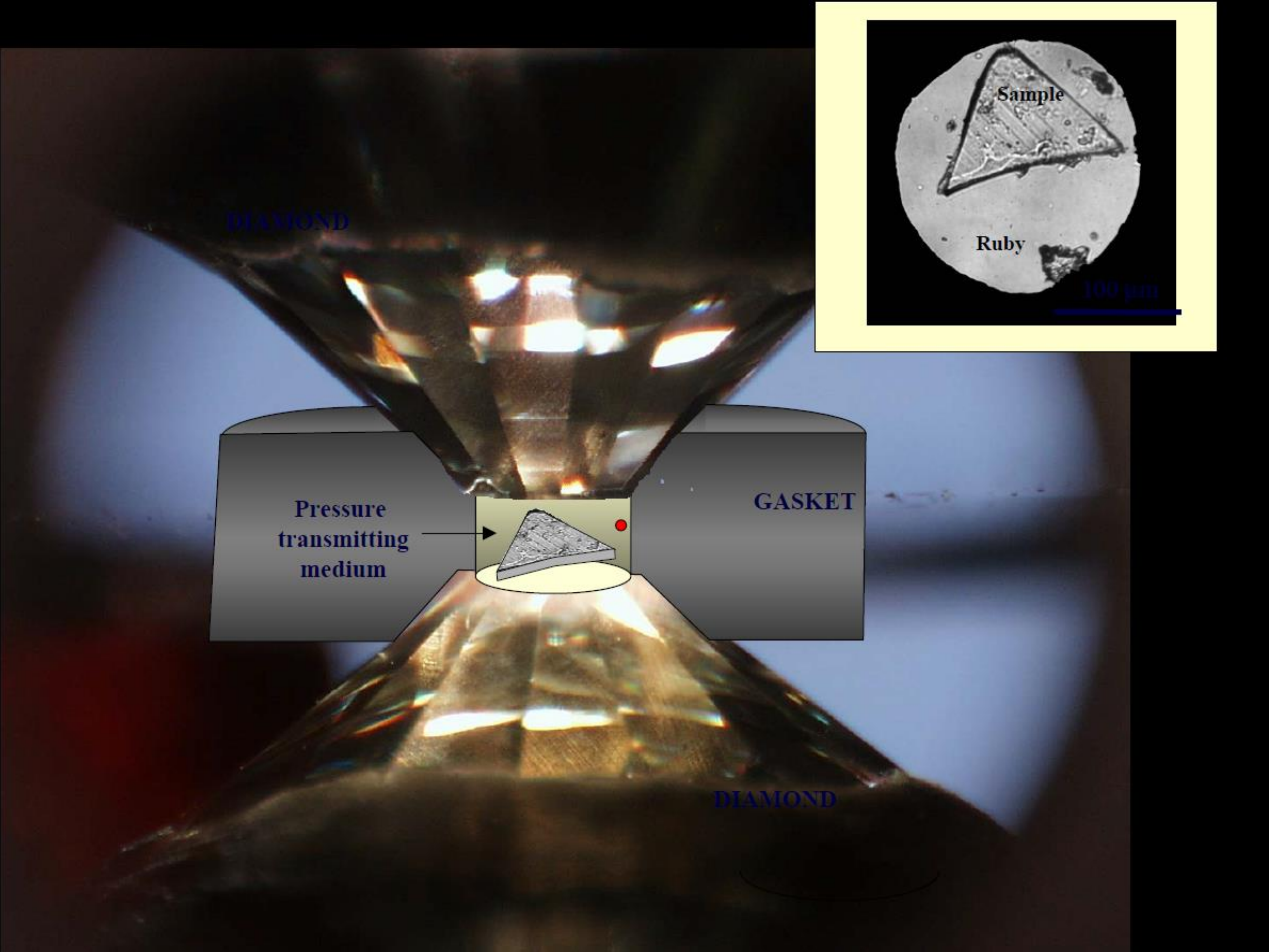
Diamond Anvil Cells

Membrane type cell

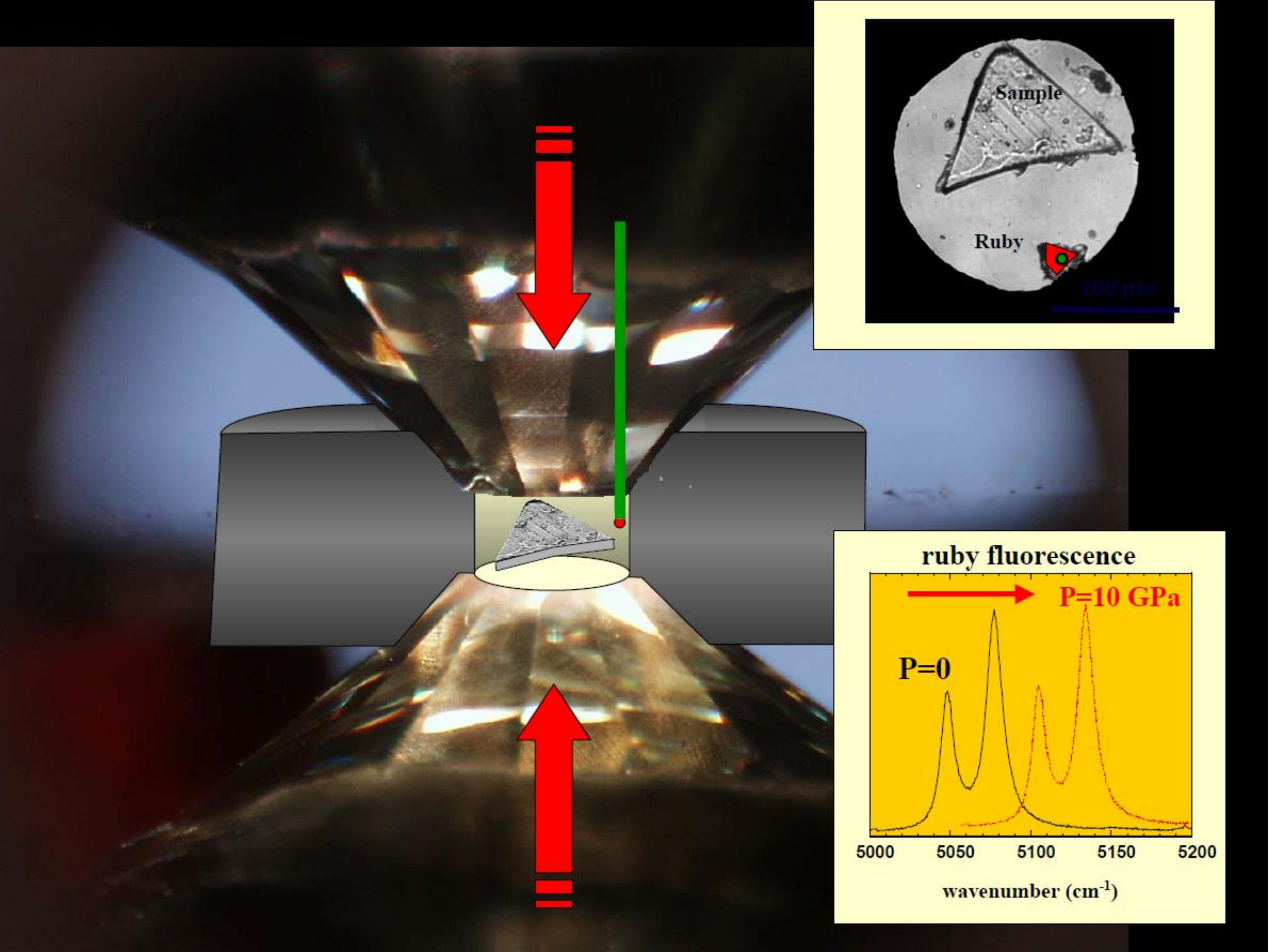


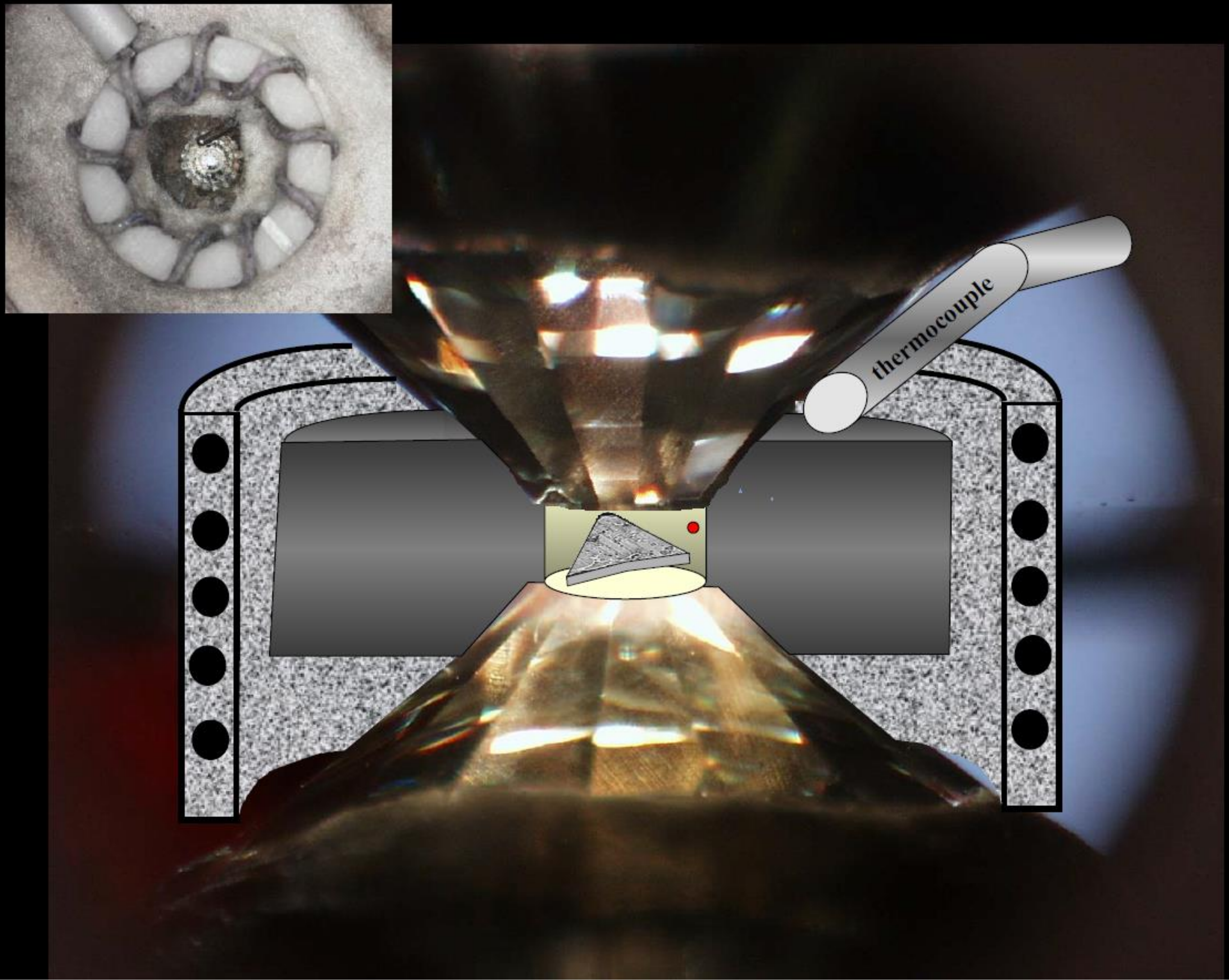
Mao-Type cell

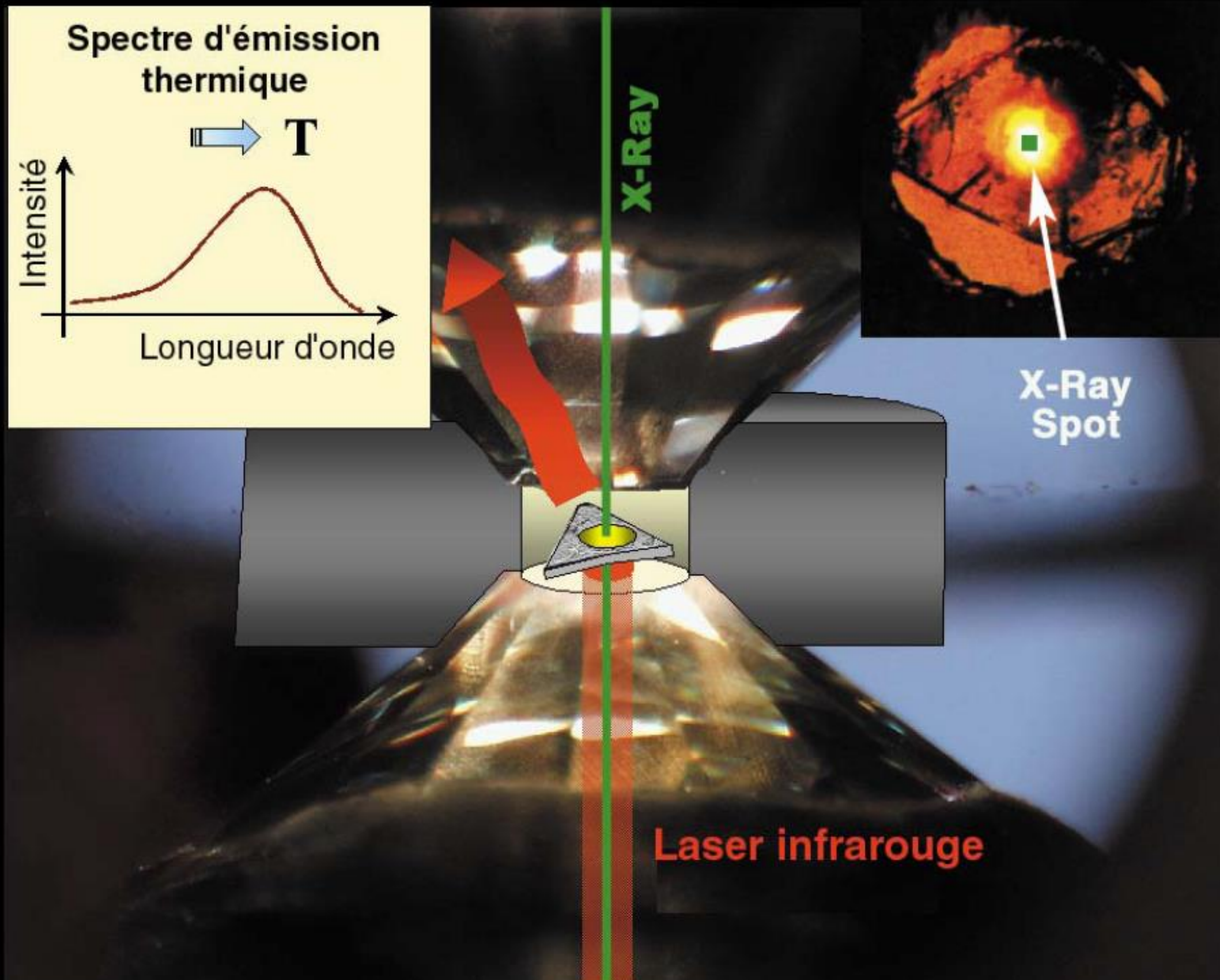




DIAMOND
Sample
Ruby
100 μm
GASKET
Pressure
transmitting
medium
DIAMOND

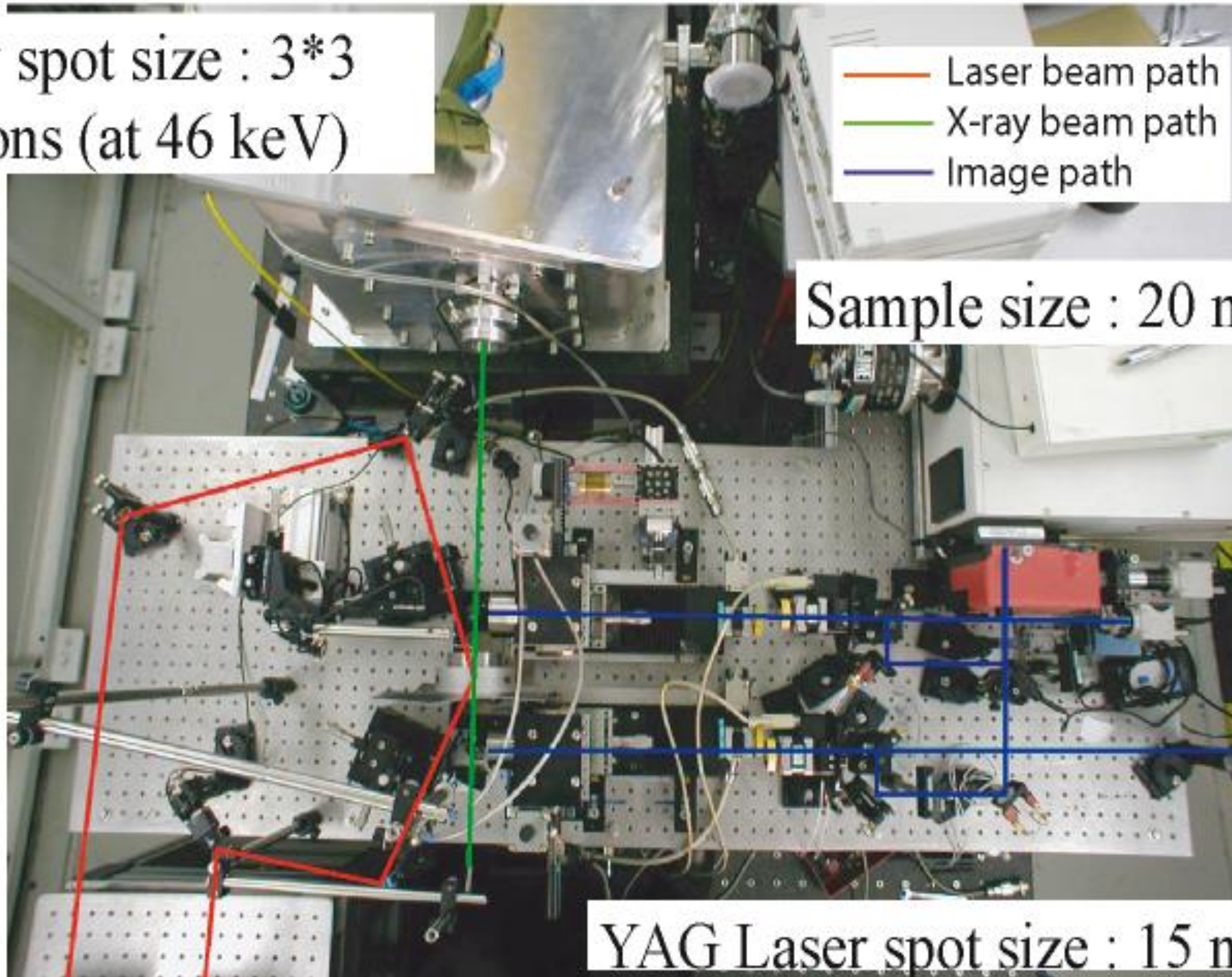

Sample
Ruby
100 μm
ruby fluorescence
P=10 GPa
P=0
5000
5050
5100
5150
5200
wavenumber (cm^{-1})


thermocouple



Spectre d'émission thermique
T
Intensité
Longueur d'onde
X-Ray
X-Ray Spot
Laser infrarouge

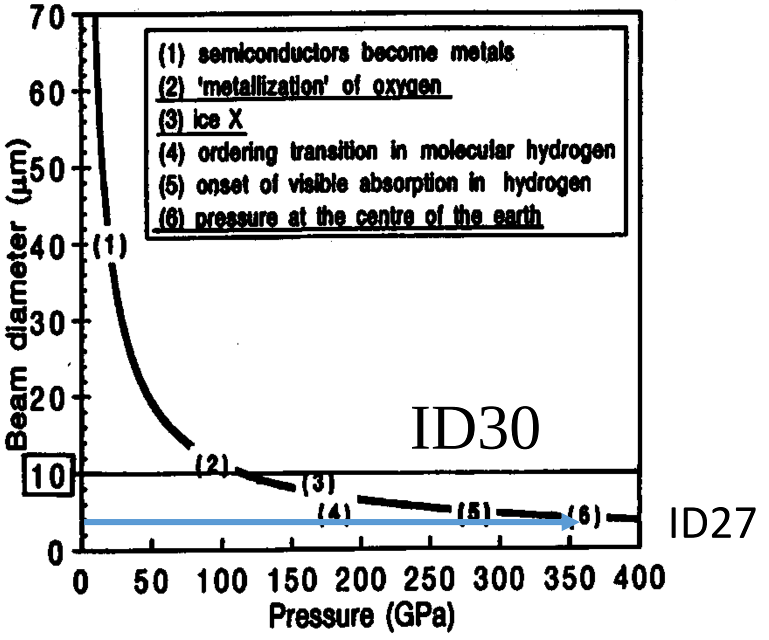
Double Sided Laser Heating DAC Experimental Set up



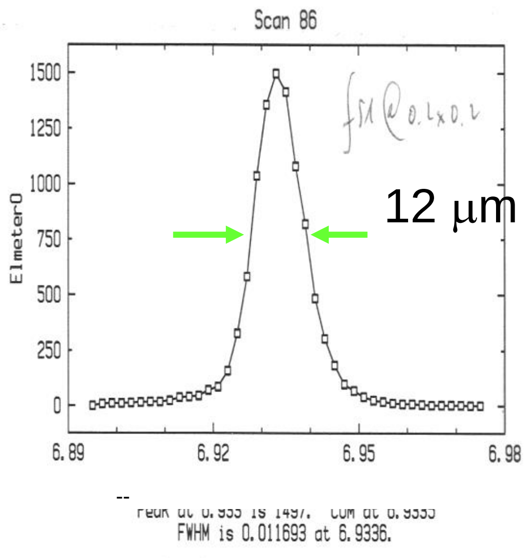
Exposure time : 20 s

High pressure beamline at the ESRF

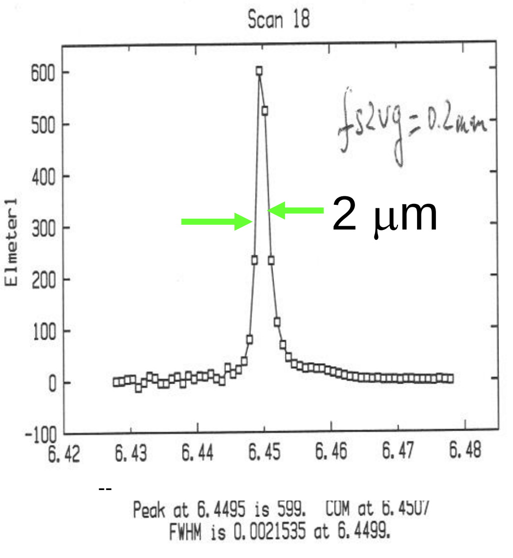
Change in the beamsize and in the X-ray flux



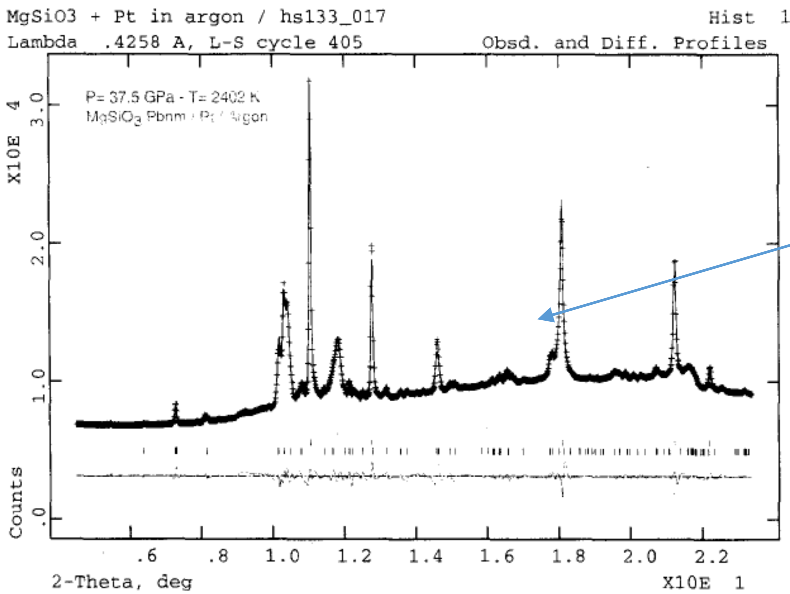
1997-2005
ID30



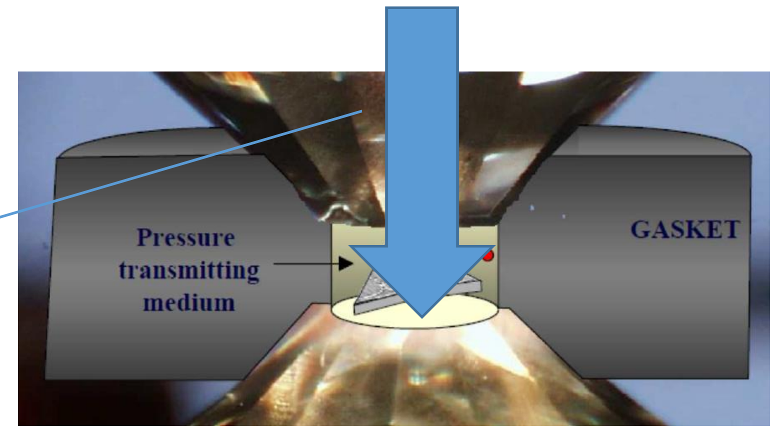
Since 2006
ID27



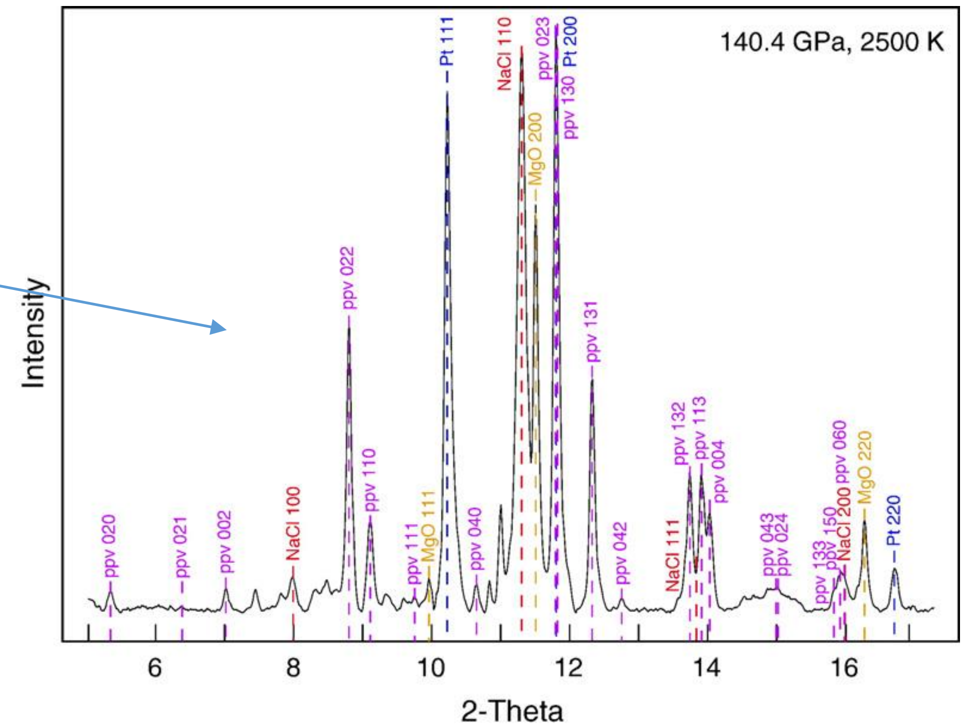
Fiquet et al, PEPI, 1998



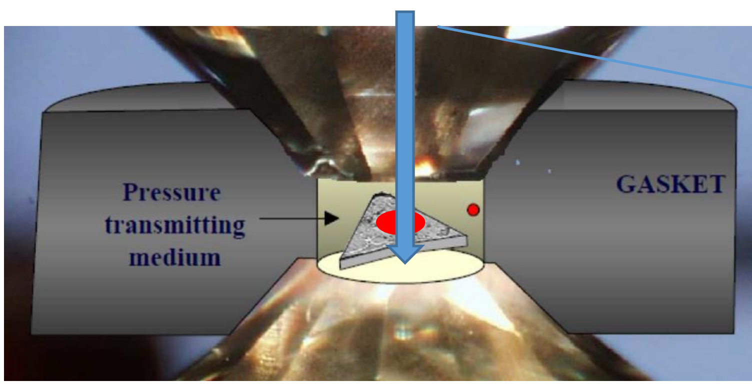
X-ray 1998



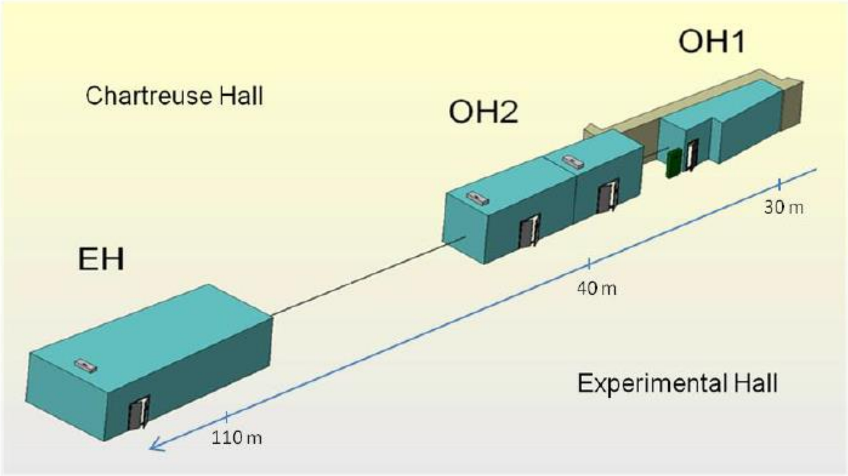
Guignot et al, EPSL, 2007



X-ray, 2007

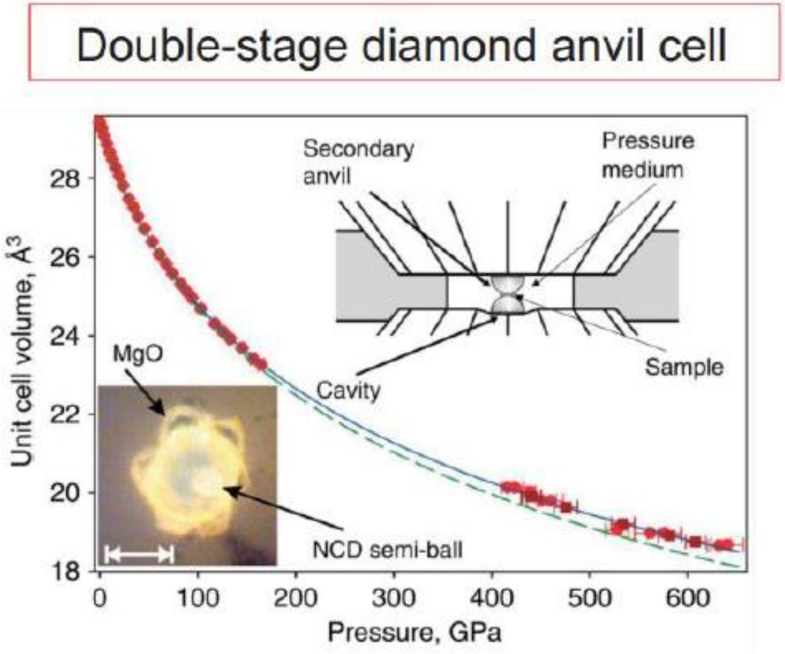


ESRF upgrade : new ID27 beamline



200 * 300 nm beam
Planned in September 2021

Over 1 000 Gpa using Diamond Anvil Cell



Dubrovinsky et al., Nat. Comm., 2013

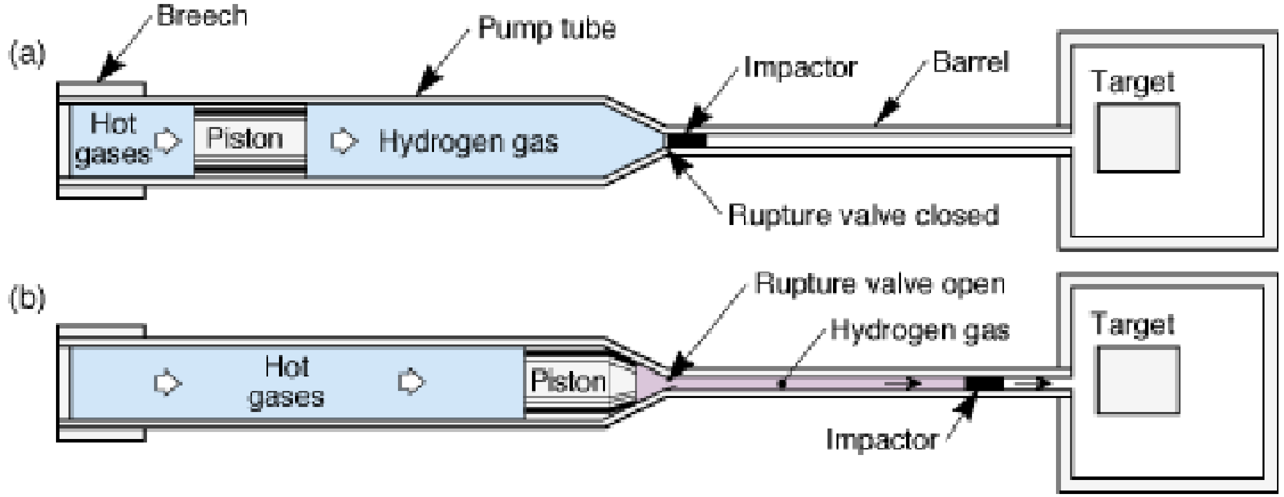
Dynamic compression experiments

Different ways to generate a shock

Explosive set-up

Different ways to generate a shock

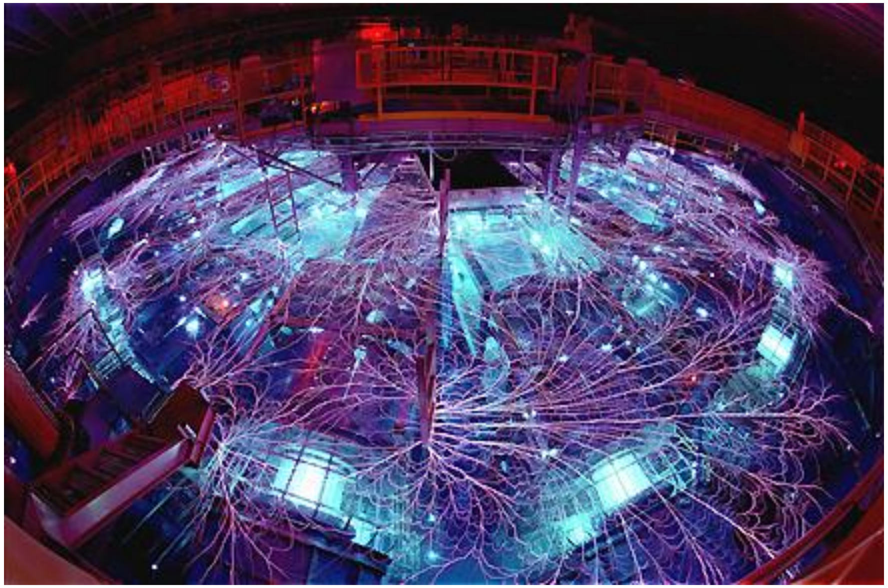
Gas-gun experiments

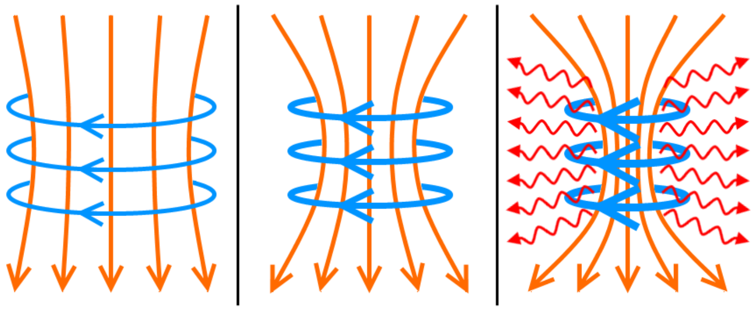


From Lawrence Livermore National Laboratory website

Different ways to generate a shock

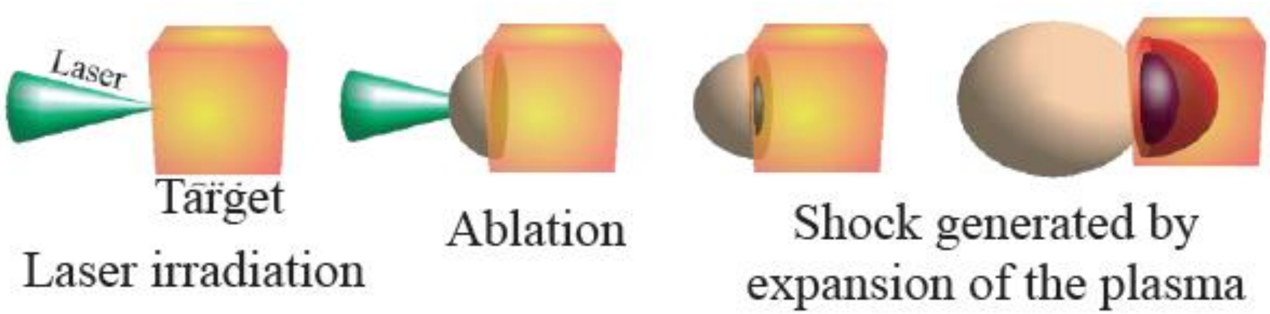
Z-pinch experiments

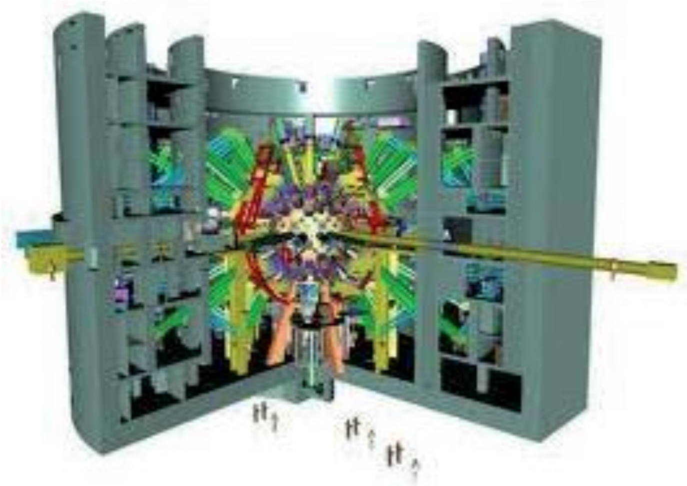




Different ways to generate a shock

Laser shock experiments

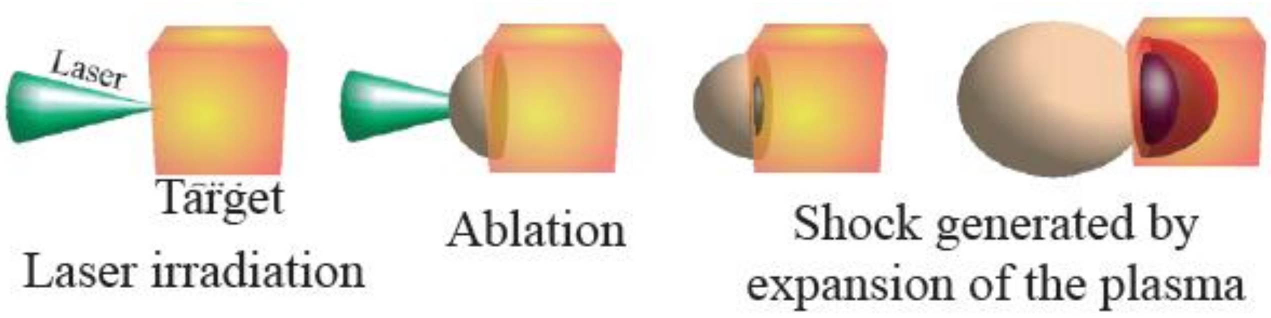


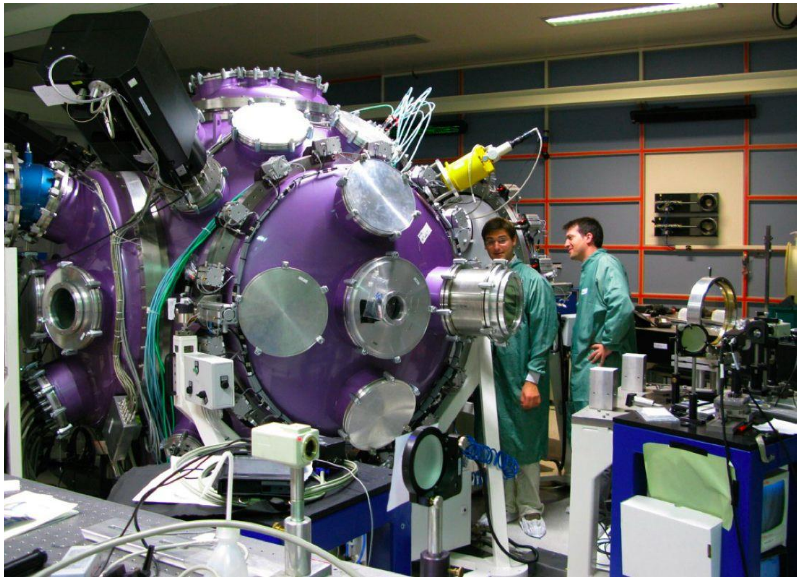


One example : MegaJoule laser, under construction, Bordeaux, France

Different ways to generate a shock

Laser shock experiments

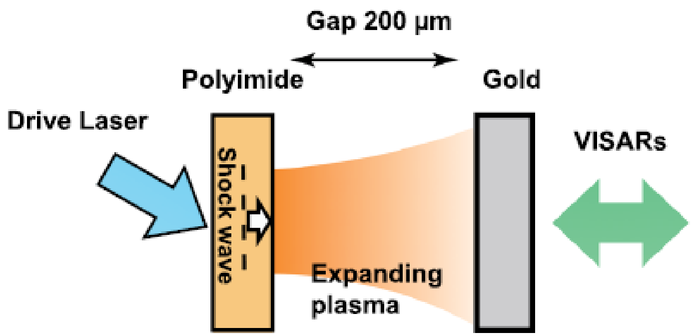


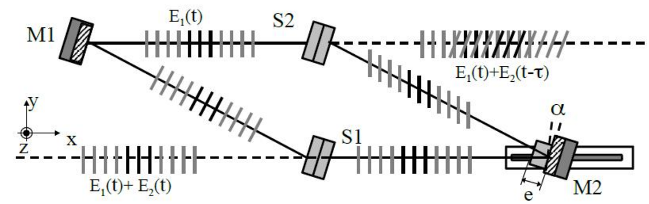


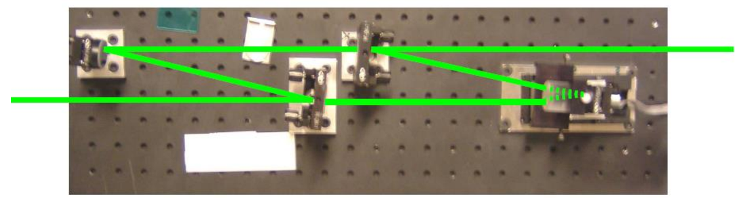
LULI 2000, Ecole Polytechnique, Palaiseau, France

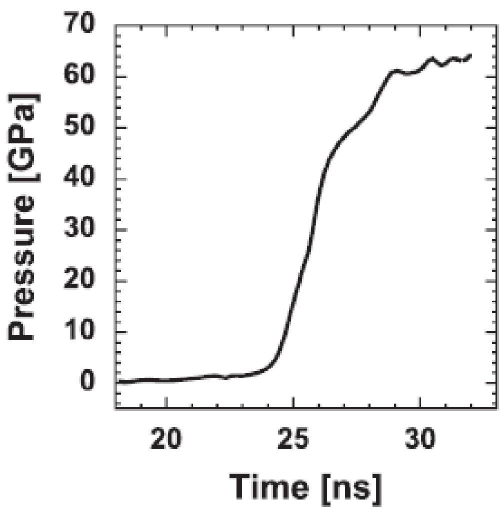
Casual diagnostic in shock experiments

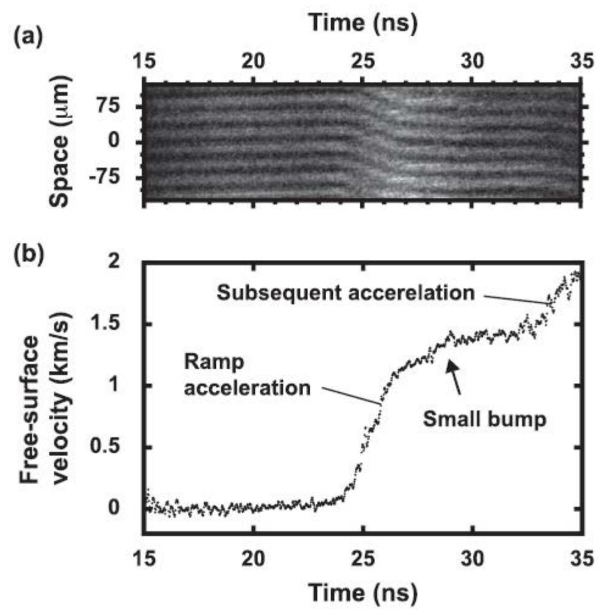
Velocity Interferometer for Any Reflector (VISAR)











From Miyanishi et al, J. App. Phys., 2014

Casual diagnostic in shock experiments

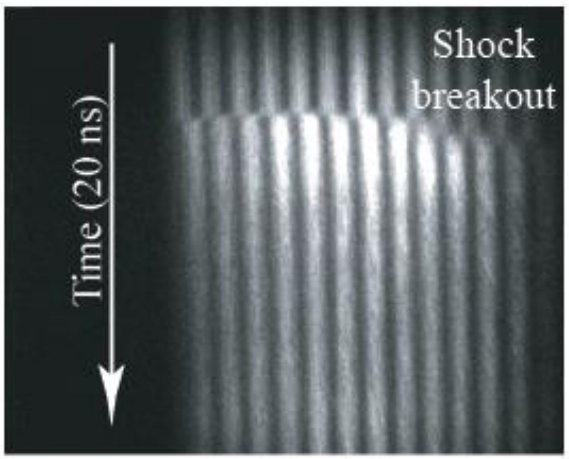
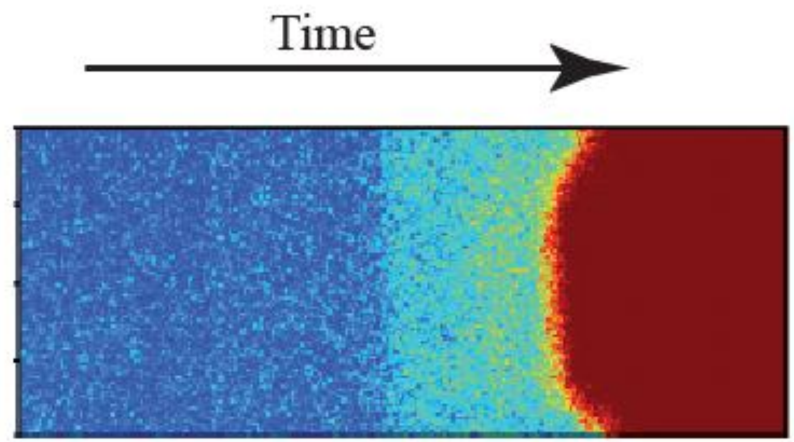


Image of interferometry of the rear face (VISAR)

Related to the pressure

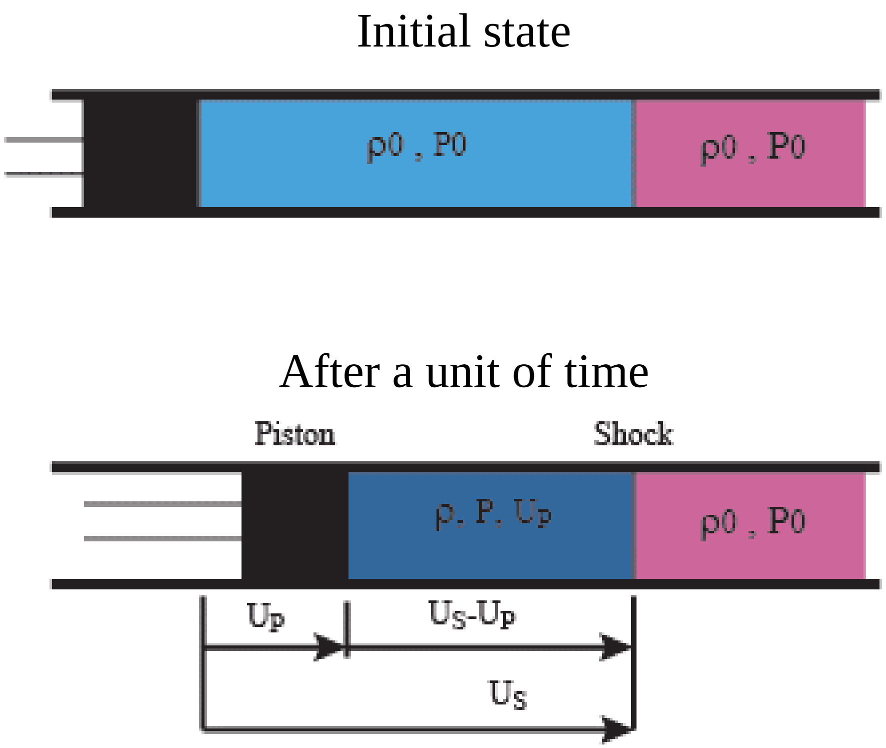


Streaked Optical Pyrometer

Related to the temperature

VISAR + SOP +…. X-ray diagnostics !!!

The conservation laws for a single shock

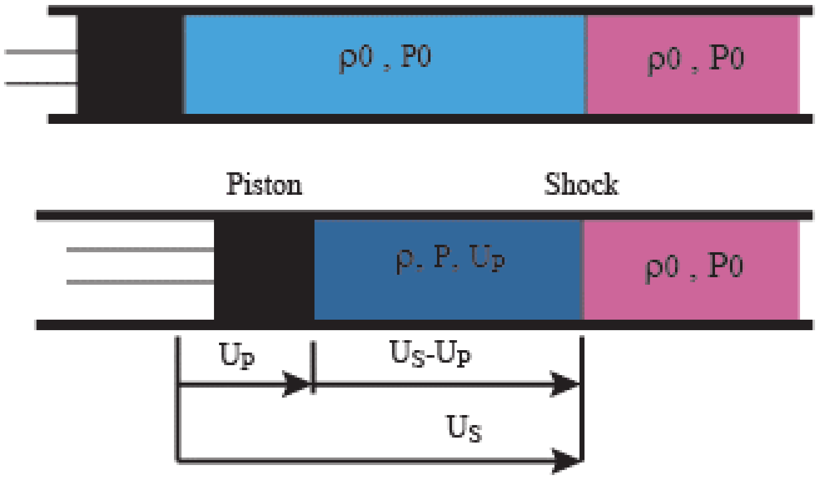


U_P : Piston velocity
U_S : Shock front velocity
A : Piston surface

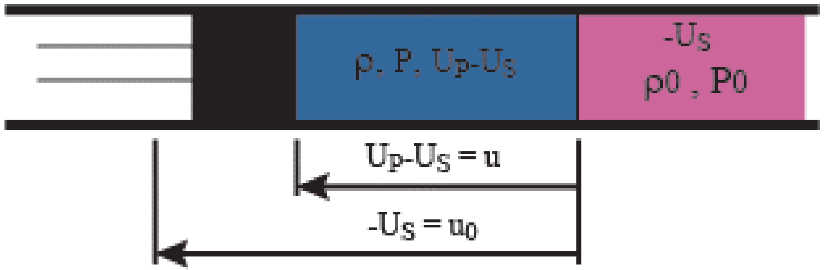
From Henderson, Handbook of shock waves, 2001

The conservation laws for a single shock

Initial state



Shock fixed coordinates



From Henderson, Handbook of shock waves, 2001

The Rankine-Hugoniot equations

- Conservation of mass

$$\rho u = \rho_0 u_0$$

- Conservation of momentum

$$p + \rho u^2 = p_0 + \rho_0 u_0^2$$

- Conservation of energy

$$\frac{p}{\rho} + e + \frac{1}{2}u^2 = \frac{p_0}{\rho_0} + e_0 + \frac{1}{2}u_0^2$$

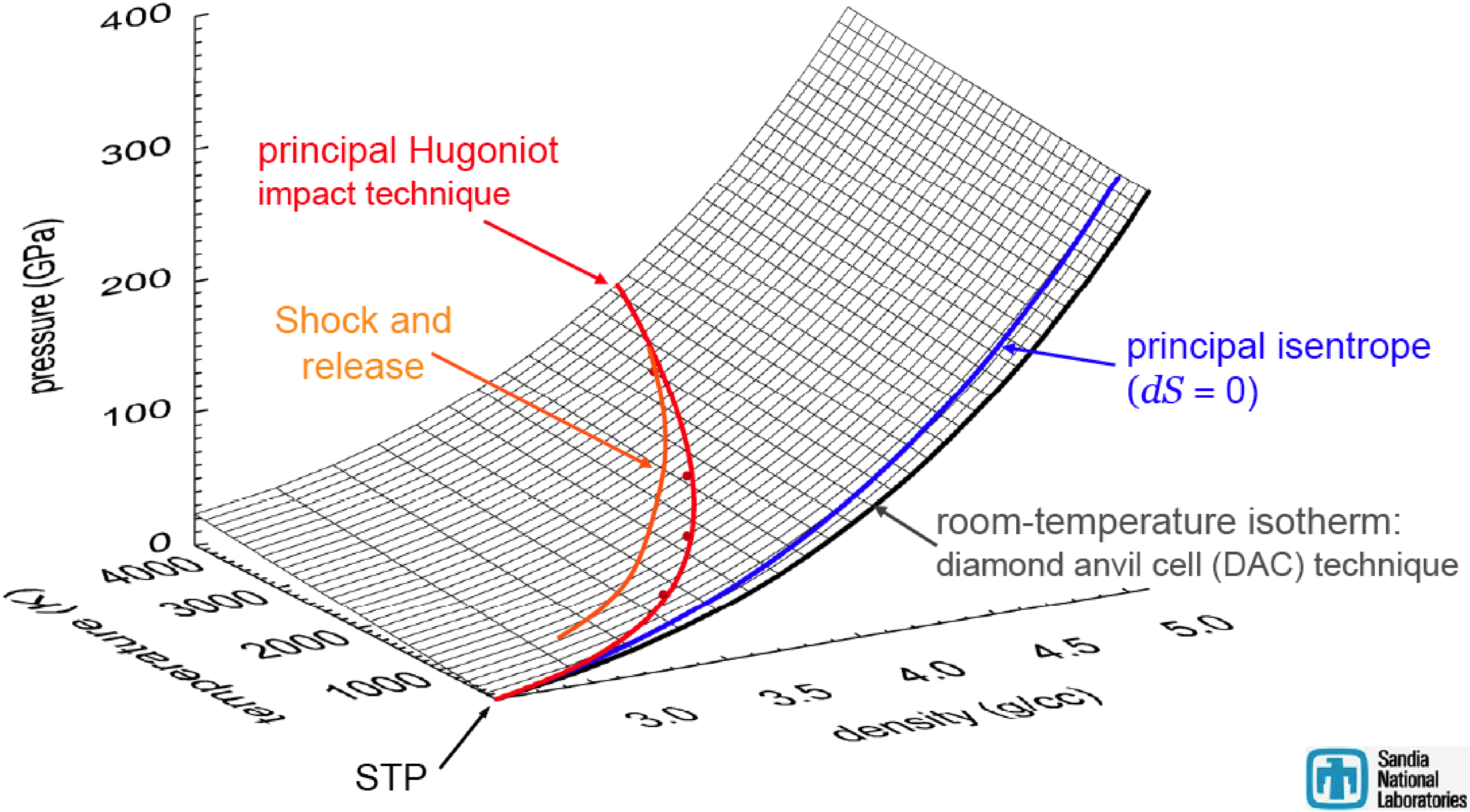
The Hugoniot equation

By removing velocities from the Rankine-Hugoniot equations, we obtain the Hugoniot equation

$$e - e_0 = \frac{1}{2}(P + P_0)\left(\frac{1}{\rho_0} - \frac{1}{\rho}\right) = \frac{1}{2}(P + P_0)(V_0 - V)$$

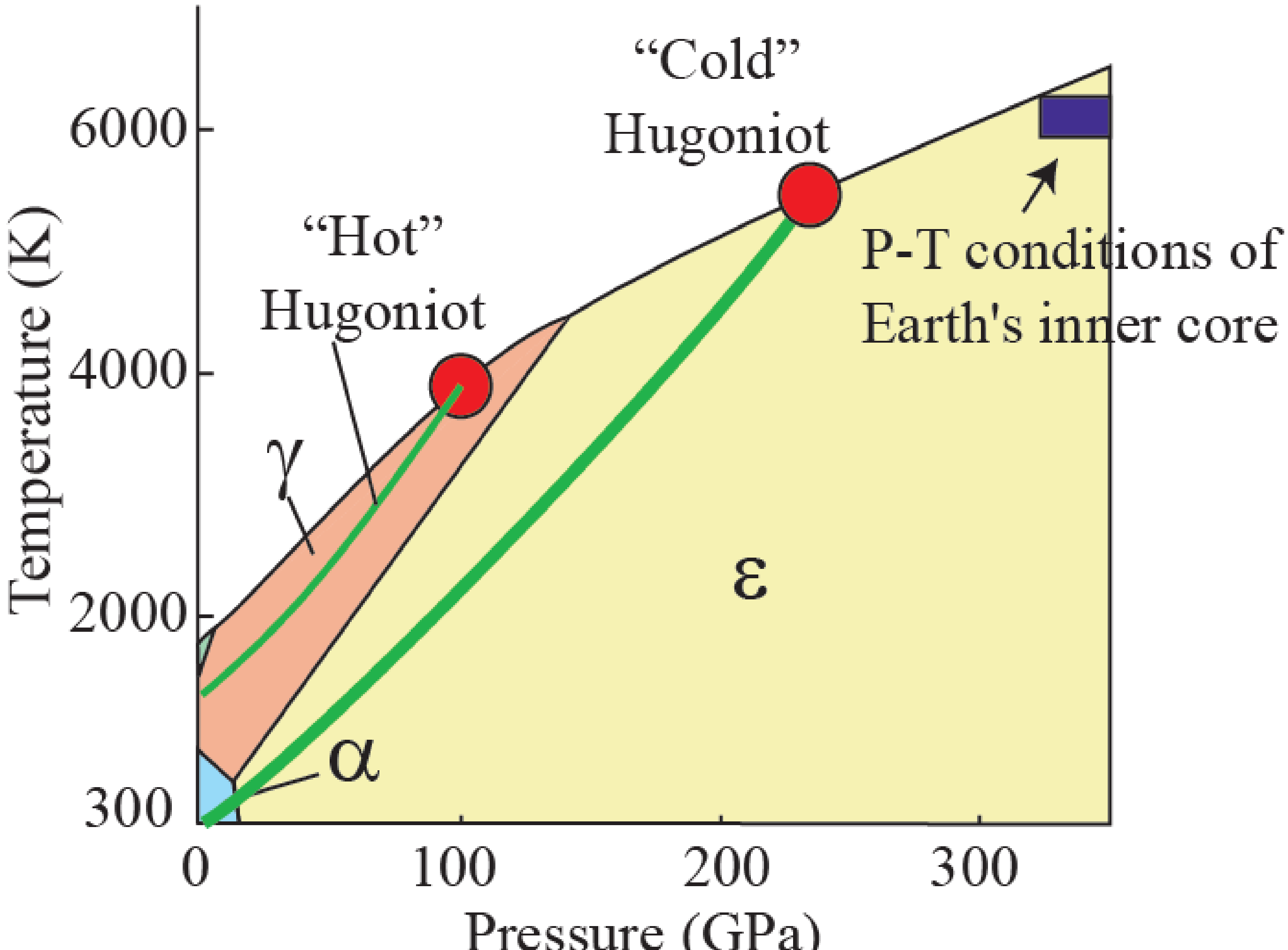
1- In the (P,ρ) space, the Hugoniot equation defines a line of possible state during the shock

2- Thermodynamic of the shock strongly depends on initial conditions (P_0,V_0)

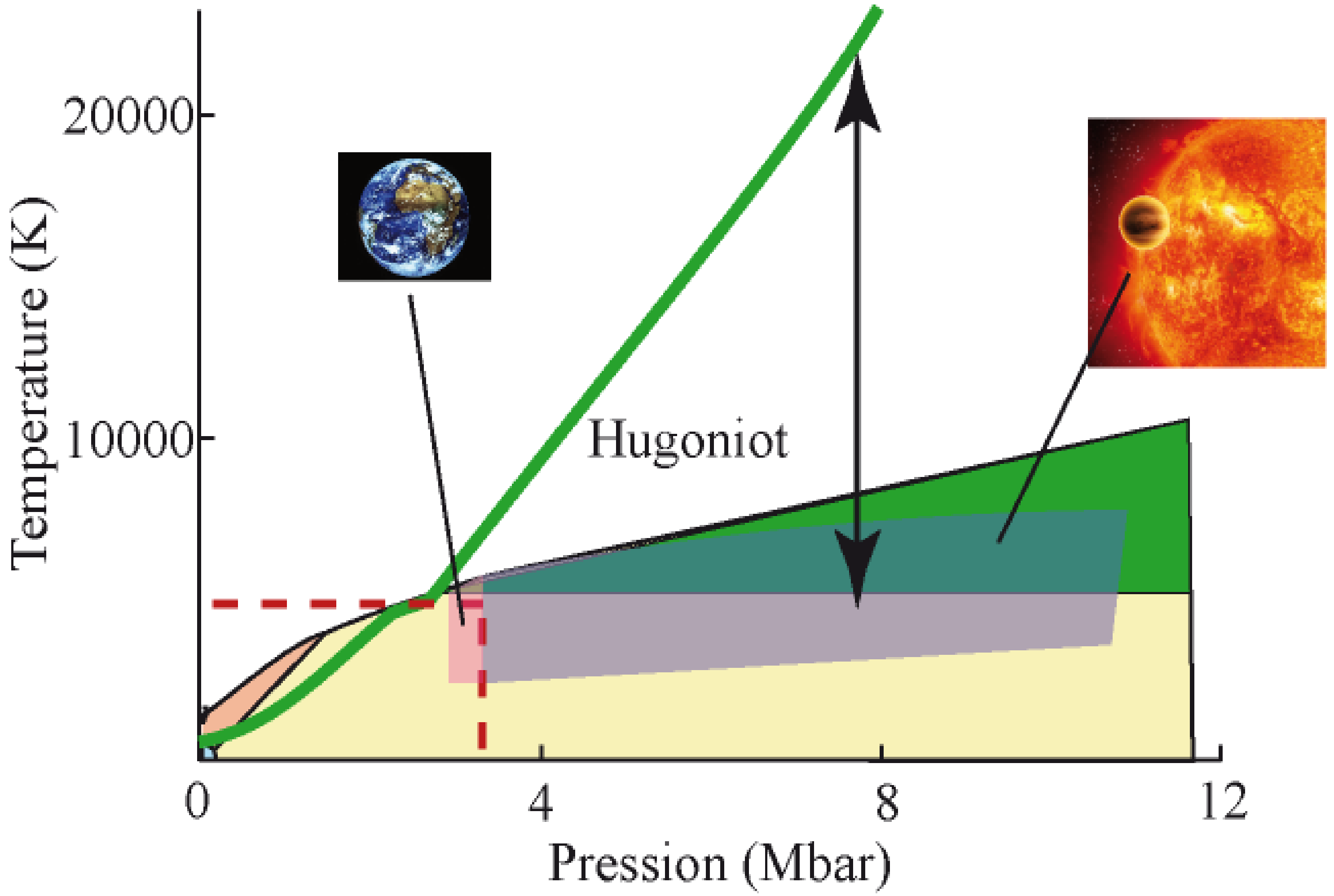


P, V, T path during shock experiments

Shock experiments on iron



Iron phase diagram under exoplanets' core conditions



A complementary technique to probe iron under extreme conditions

Experiments

Calculations

Molecular dynamics calculations

Molecular dynamics calculations performed using ABINIT code

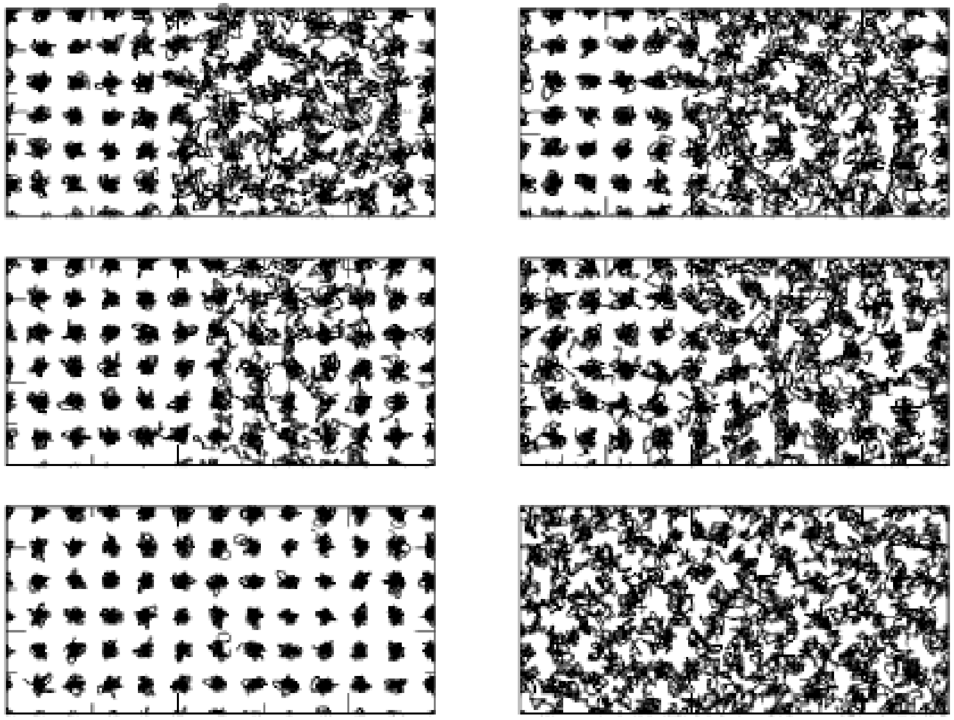
PAW method for calculation of electronic structure

The electrons are treated quantum mechanically using the DFT

GGA method for the exchange-correlation energy and potential

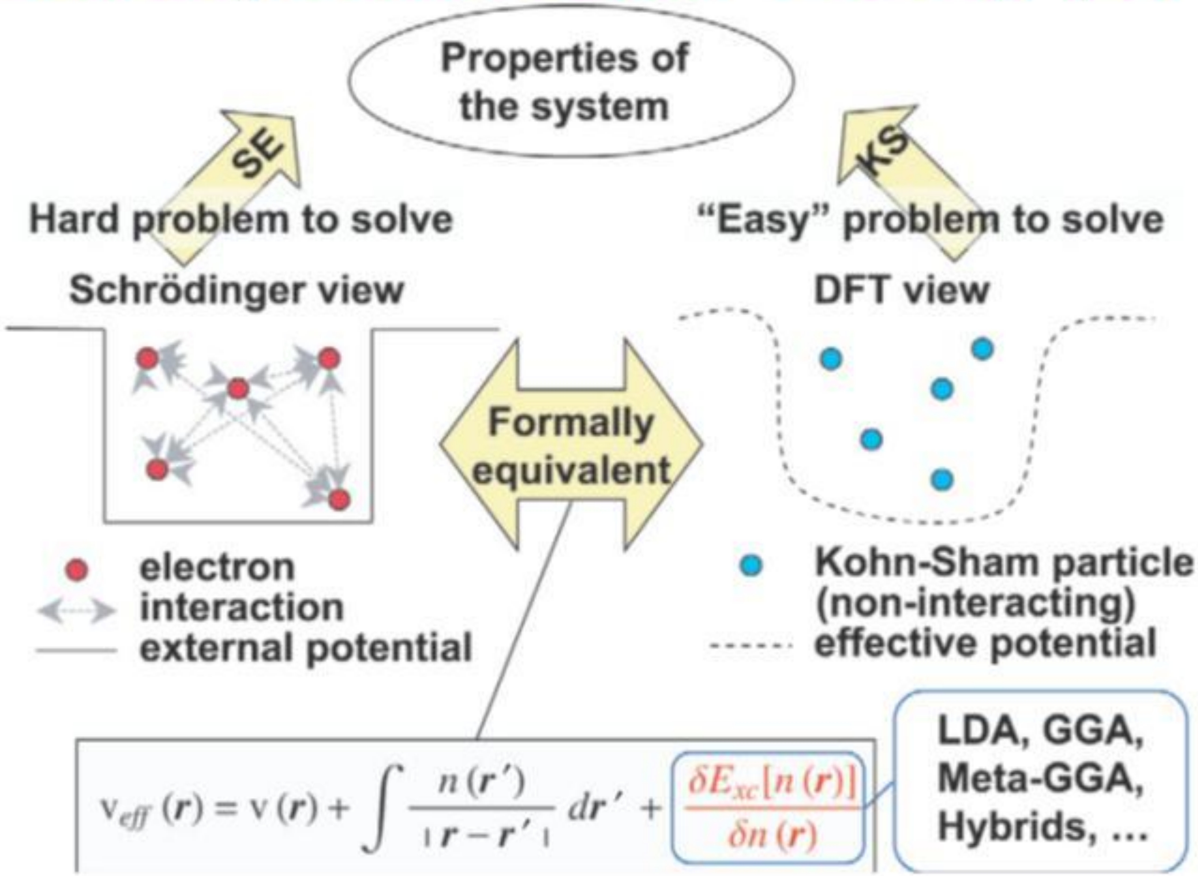
NVT method

256 atoms



Pure Fe melting temperature calculated using the coexistence method

Density Functional Theory (DFT)



Mattsson, et al., Simulation in Materials Science and Engineering, 13 (2005)