Fast electron generation and transport in laser-induced shock compressed plasmas

João Jorge Santos
CELIA, Université de Bordeaux, France

on behalf of the **experimental validation program of the inertial fusion energy project (HiPER - WP10)**

Fast electron propagation in warm dense plasmas obtained by

A) laser-driven planar compression

1st experiment at LULI2000, March 2008

D. Batani (PI), P. Carpeggiani, M. Veltcheva — *Univ. Milano-Bicocca, Italy*

F. Dorchies, A. Dubrouil, E. d'Humières, C. Fourment, S. Hulin, Ph. Nicolaï, J.J. Santos, V. Tikhonchuk — *CELIA, Univ. Bordeaux, France*

P. McKenna, M.N. Quinn — *SUPA, Univ. Strathclyde, Glasgow, UK*

S.D. Baton, E. Brambrink, M. Rabec Le Gloahec — *LULI, Ecole Polytechnique, France*

Ch. Spindloe, M. Tolley — *RAL, UK*

L. Gremillet — *CEA-DAM-DIF, France*

A. Debayle, J.J. Honrubia — *ETSI Aeronauticos, Univ. Politécnica de Madrid, Spain*

2nd experiment at LULI2000, April 2010

J.J. Santos (PI), F. Dorchies, C. Fourment, S. Hulin, Ph. Nicolaï, V. Tikhonchuk, X. Vaisseau, B. Vauzour — *CELIA, Univ. Bordeaux, France*

S.D. Baton, E. Brambrink, F. Perez, H.-P. Schlenvoigt, V. Yahia — *LULI, Ecole Polytechnique, France*

D. Batani, R. Benocci, L. Volpe — *Univ. Milano-Bicocca, Italy*

M. Coury, P. McKenna — *SUPA, Univ. Strathclyde, Glasgow, UK*

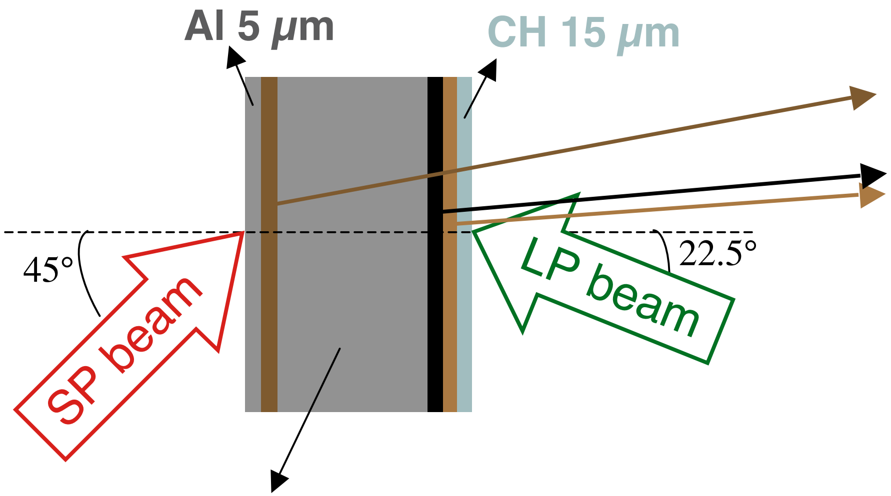
F.N. Beg, S. Chawla, L.C. Jarrot — *UCSD, USA*

Y. Rhee — *KAERI, Rep. Korea*

Fast electron transport in 1D compressed foil targets:
Principle of the experiment

A flat foil target is compressed by a long pulse beam (LP)
— 250J, 5ns, 0.53μm, 3x10^{13} Wcm^{-2}, 400μm focal spot (flat-top)

A fast electron jet is generated by a short pulse beam (SP)
— ~30J, 1ps, 1.06μm, 5x10^{18} Wcm^{-2}, gaussian focal spot 10μm (FWHM)



fluorescent layers

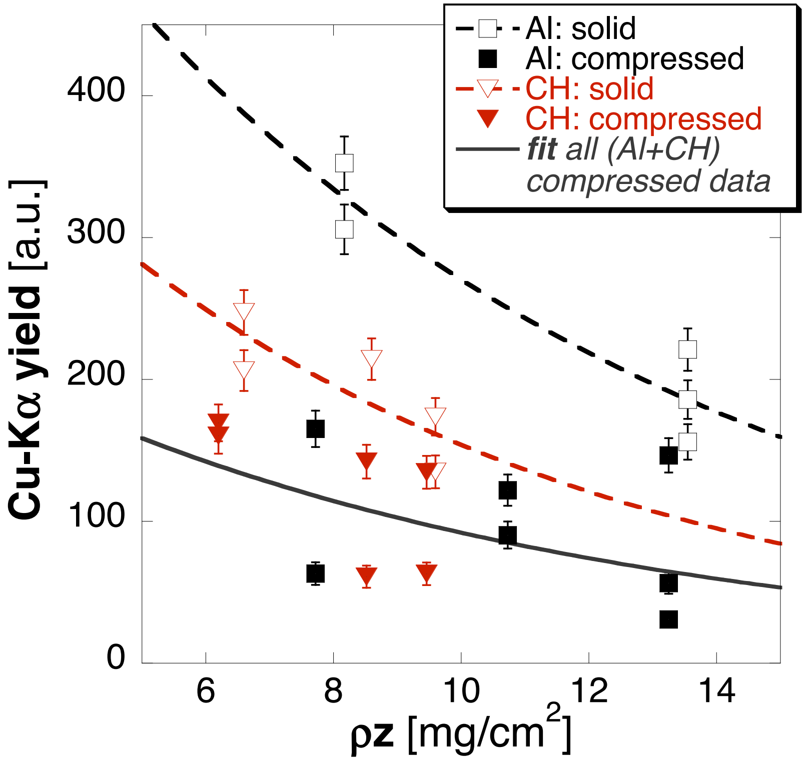
Ag 5 μm on the front side
(signature of the fast electron source)

Sn 10 μm + **Cu 10 μm** on the rear side
(signature of the fast electrons reaching the rear side)

propagation layer
Al variable thickness
10, 20, 40, 60, 80 μm

- Delay SP/LP adjusted to allow the full compression of the ≠ Al propagations layers
- Results in compressed targets ($\rho / \rho_0 \sim 2$; $T_e \sim 4$eV) are compared to solid cold targets
- Also tested for CH propagation layers (in 2008)

Cu-Kα yields measured by spectroscopy in 2008: differences Al / CH ascribed to collective mechanisms



Without compression,
yields are higher for Al than for CH targets

➡ ***Electric field inhibition of the fast electron propagation in cold CH layers***

With compression,
yields are comparable between Al and CH

➡ ***Both layers are partially ionised and behave like a conducting plasma*** *(same Z* and n_e)*

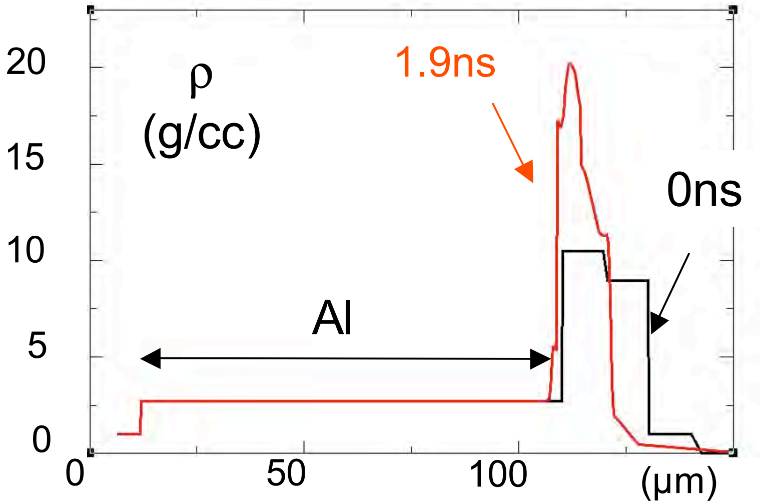
When comparing solid to compressed targets, CH becomes a conductor and Al becomes more resistive (heated to ~4eV, near the Fermi temperature)

! ***But these effects are masked by electron refluxing in the solid case !***

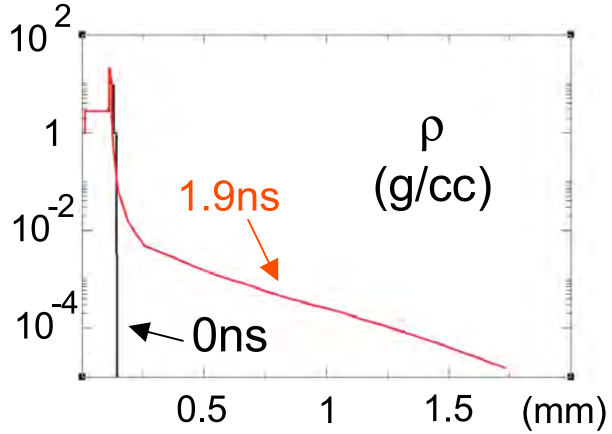
Cf. J.J. Santos *et al.*, PPCF **51**, 014005 (2009)

How to study fast electron transport in solid propagation layers without electron refluxing ?

➡ ***Always shoot the long pulse but inject the short pulse at early times, just before the shock enters the Al propagation layer***



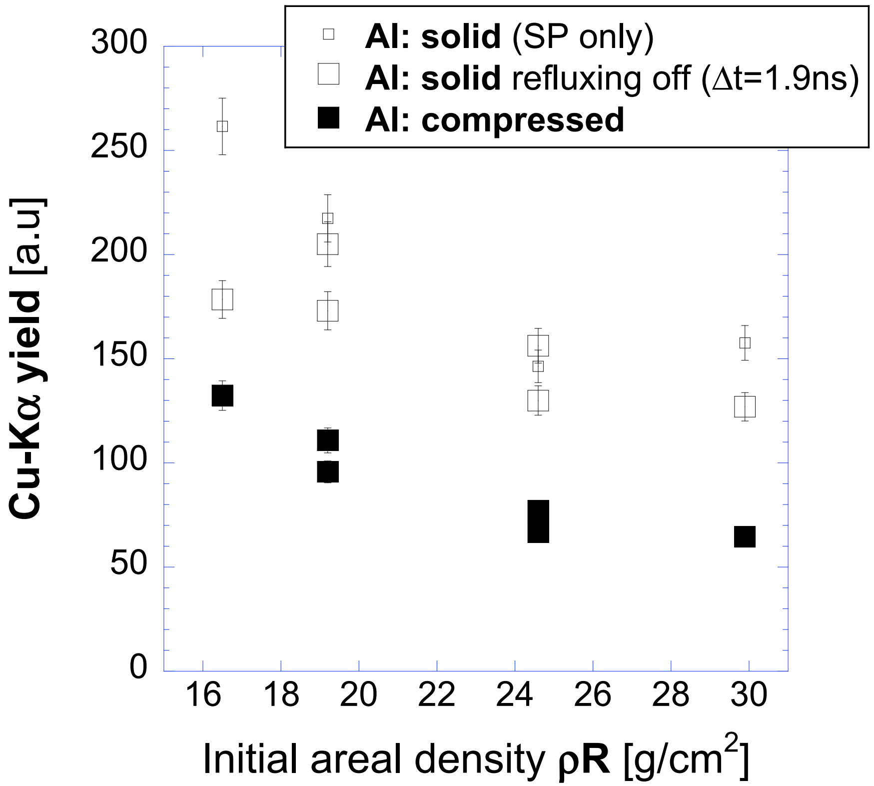
Zoom of the rear side plasma :



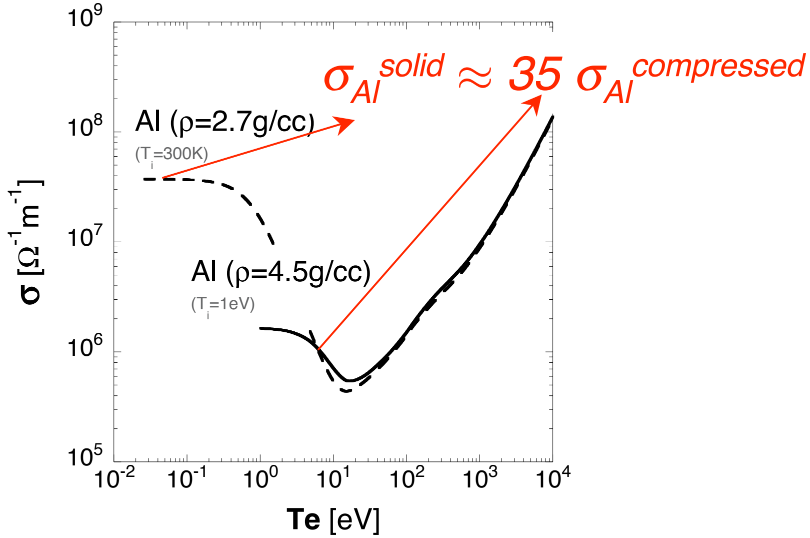
The LP beam creates a several 100s μm-long coronal plasma at the target's rear side

➡ ***Inhibition of the electrons re-injection into the dense target depth !***

Preliminary results from the 2010 experiment:
Inhibition of electron transport in warm compared to cold Al



1D shock ⇒ ρR not changed upon compression
⇒ changes due to collective mechanisms



According to hybrid simulations of the fast electron transport :
(cf. A. Debayle, J.J. Honrubia)

➡ ***Changes in collective stopping power between solid and compressed Al are appreciable for incident fast electron current in the range $10^{10} < j_h < 10^{12}$ Acm^{-2}***

➡ *Need to* ***explore the parameters*** *of the fast electron source (emissivity, source radius, energy spectrum)* ***better explaining the inhibition of the electron propagation***

Fast electron propagation in warm dense plasmas obtained by

B) laser-driven cylindrical compression

Experiment at Vulcan TAW (RAL), Oct-Dec 2008

M. Koenig (co-PI), S.D. Baton, E. Brambrink, F. Perez, A. Ravasio
— LULI, Ecole Polytechnique, France

D. Batani (co-PI), R. Jafer, L. Volpe *— Dpt. di Fisica, Univ. Milano-Bicocca, Italy*

F. Dorchies, C. Fourment, S. Hulin, Ph. Nicolaï, C. Regan, X. Ribeyre, G. Schurtz, J.J. Santos, B. Vauzour *— CELIA, Univ. Bordeaux, France*

M. Galimberti, R. Heathcote, K. Lancaster, Ch. Spindloe *— RAL, UK*

L.A. Gizzi, L. Labate, P. Koester *— ILIL at INO, CNR, Pisa, Italy*

A. Debayle, J.J. Honrubia, R. Ramis
— ETSI Aeronauticos, Univ. Politécnica de Madrid, Spain

L. Gremillet *— CEA-DAM-DIF, France*

C. Benedetti, A. Sgattoni *— Dpt. di Fisica, Univ. Bologna, Italy*

M. Richetta *— Dpt. Ing. Meccanica, Univ. di Roma Tor Vergata, Italy*

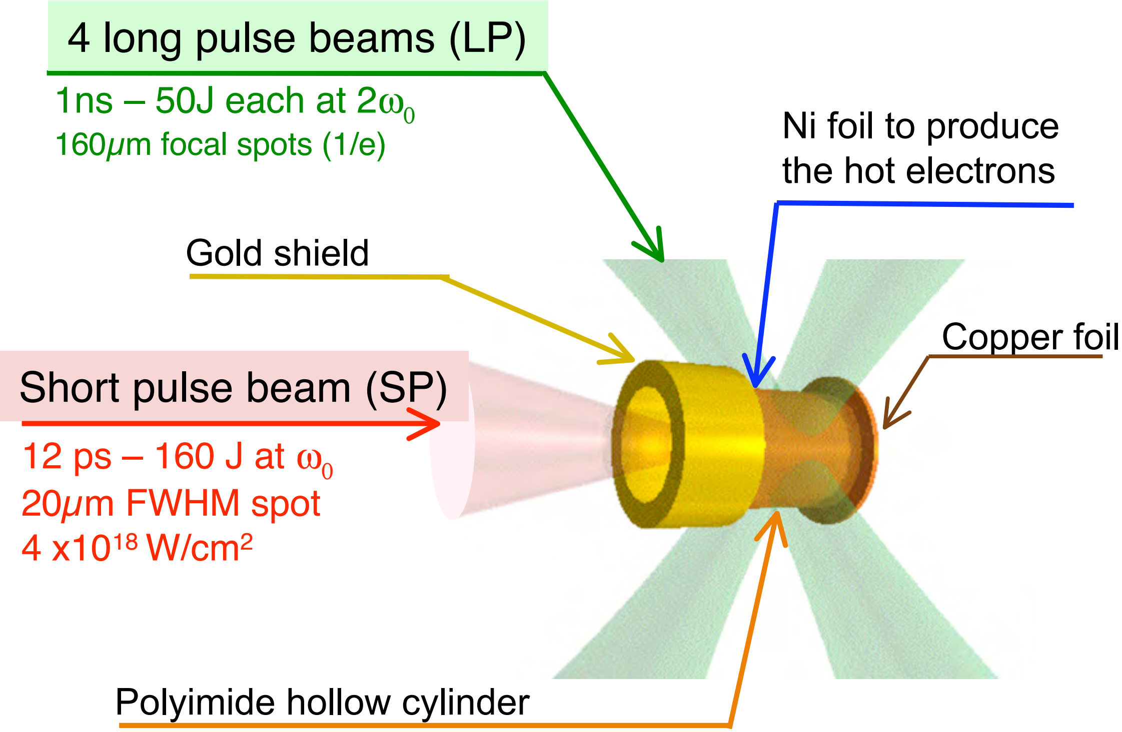
F.N. Beg, S. Chawla, D.P. Higginson *— UCSD, USA*

A.J. MacKinnon, A.G. McPhee *— LLNL, USA*

J. Pasley *— Dpt. Physics, Univ. York, UK*

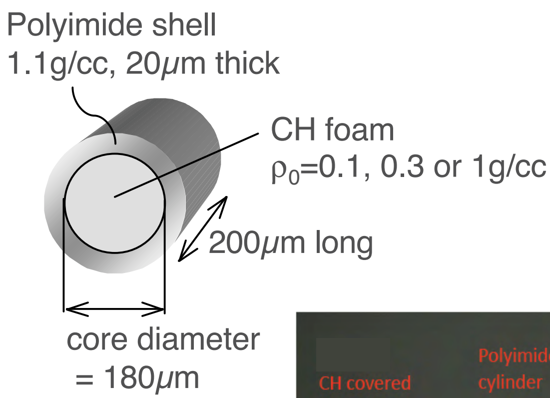
W. Nazarov *— Univ. St. Andrews, UK*

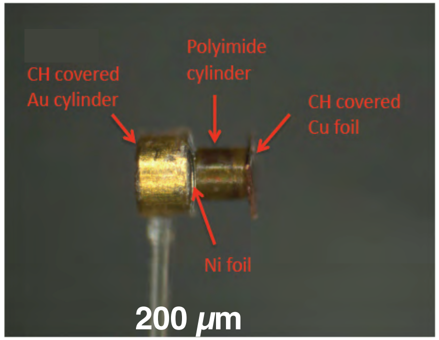
Setup overview



containing CH foam of 3 ≠ densities: 0.1, 0.3 and 1g/cc

Target description





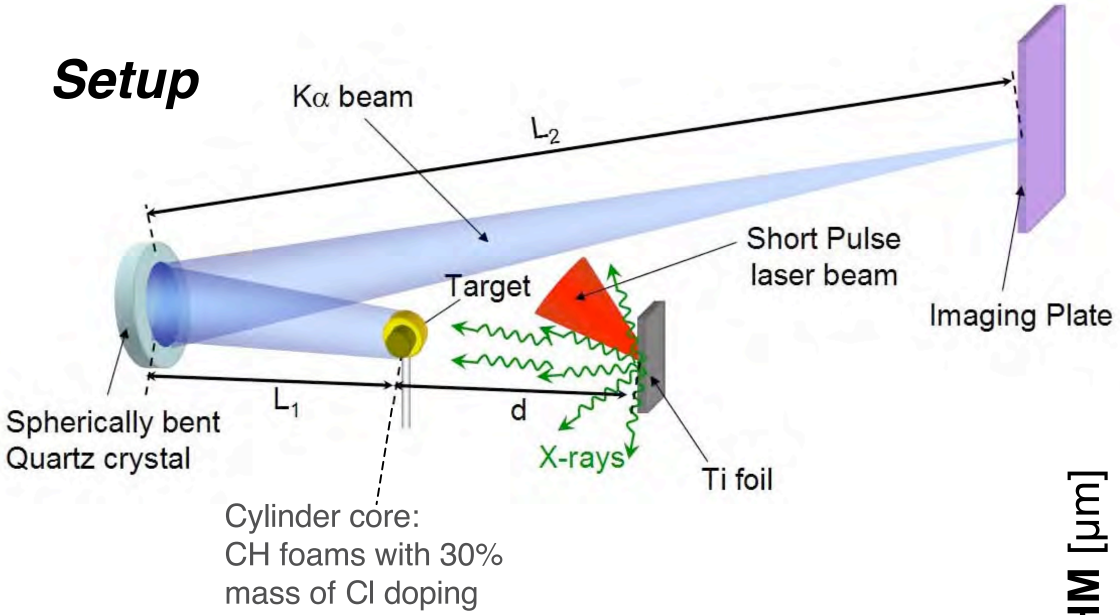
Experiment divided in two phases:

➡ **Phase 1:** study of the compression
(proton radiography, X-ray radiography)

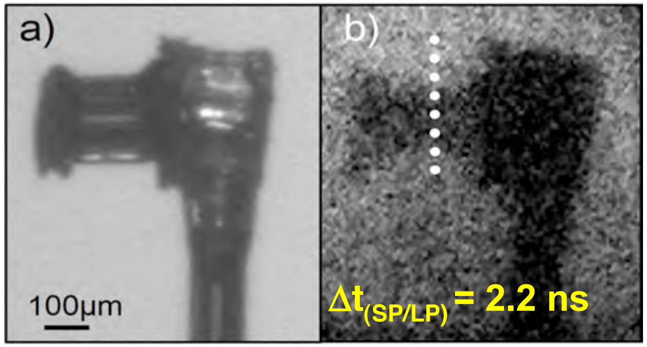
➡ **Phase 2:** study of the fast electron transport at different stages of the compression
(Cu-Kα back and side imaging, Ni and Cu-Kα spectroscopy, Bremsstrahlung cannon)

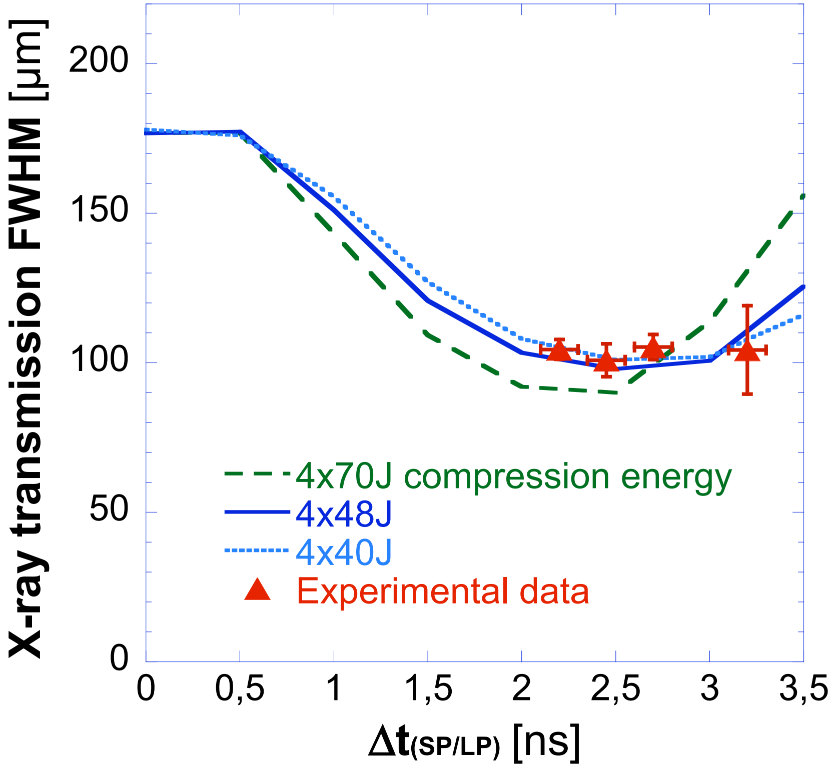
Phase 1: Study of the target implosion
X-ray radiography of $\rho_0 = 1 g/cc$ targets

Setup



Sample radiography





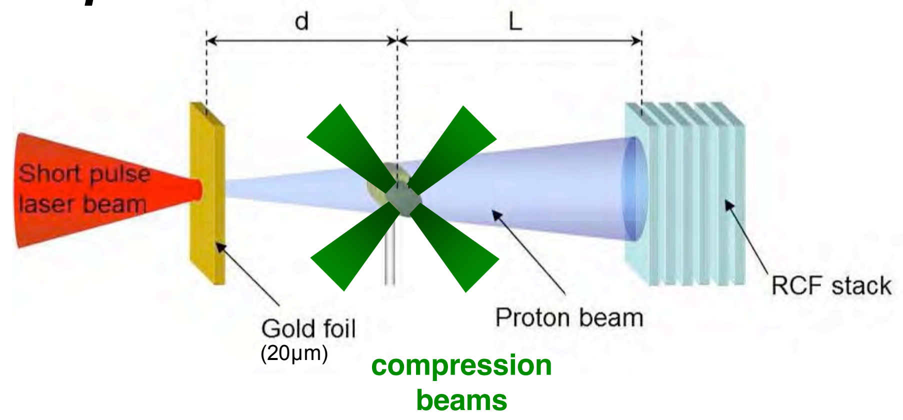
- ➡ **Cylindrical compression is visible**
- ➡ **Diameter of the X-ray transmission profiles in fair agreement with predictions from hydro simulations**
- ➡ **Stagnation time τ≈2.5ns in agreement with predictions from hydro simulations**

Cf. B. Vauzour *et al.*, to be submitted to Phys. Plasmas

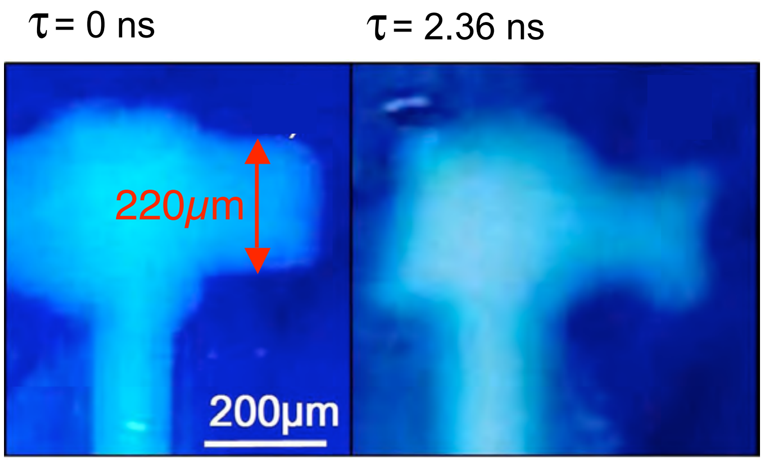
Phase 1: Study of the target implosion

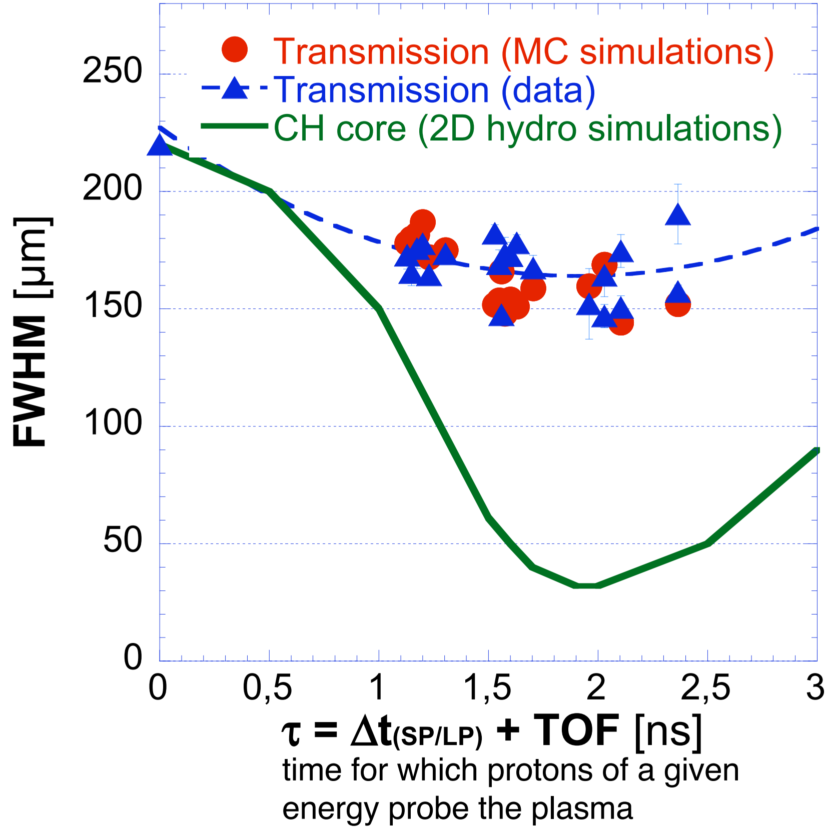
Proton radiography of $\rho_0 = 0.1$g/cc targets

Setup



RCF images show compression





➡ **Stagnation time $\tau \approx 1.9$ns in agreement with predictions from hydro simulations**

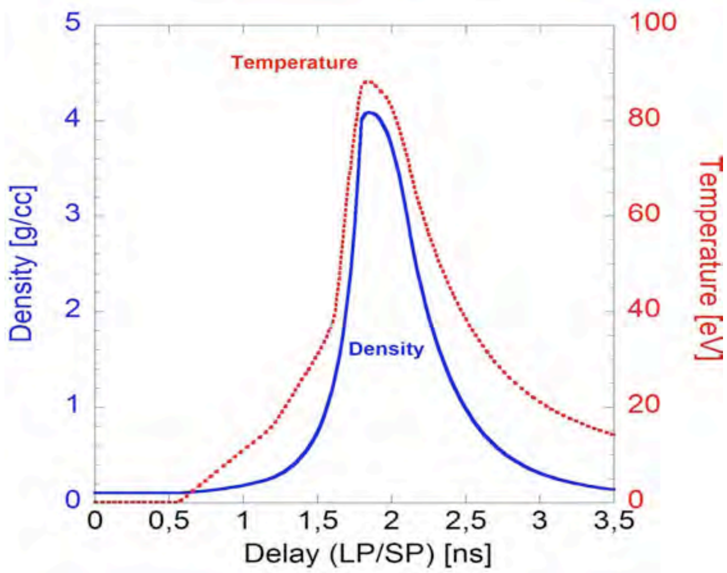
➡ **Measured cylinder diameters reproduced by MC simulations accounting for plasma effects in proton multiple scattering and stopping power**

Cf. L. Volpe *et al.*, to be submitted to PRE
B. Vauzour *et al.*, to be submitted to Phys. Plasmas

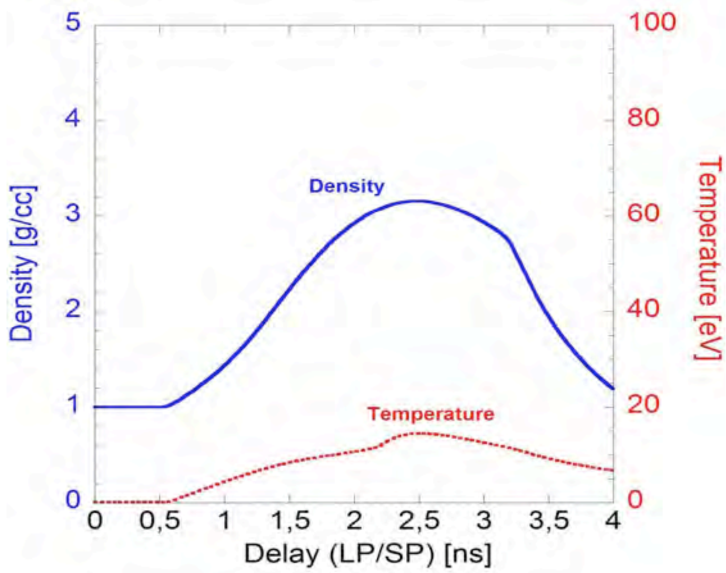
Right parameters for the hydrodynamic calculations deduced from the observed compression history ⇒ ρ and T evolution

Time-evolution of the **density** and the **temperature** at the cylinder's core axis

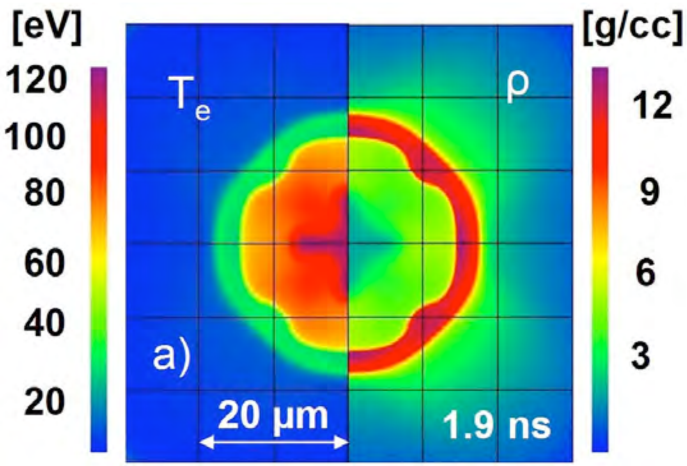
ρ_0 = 0.1g/cc

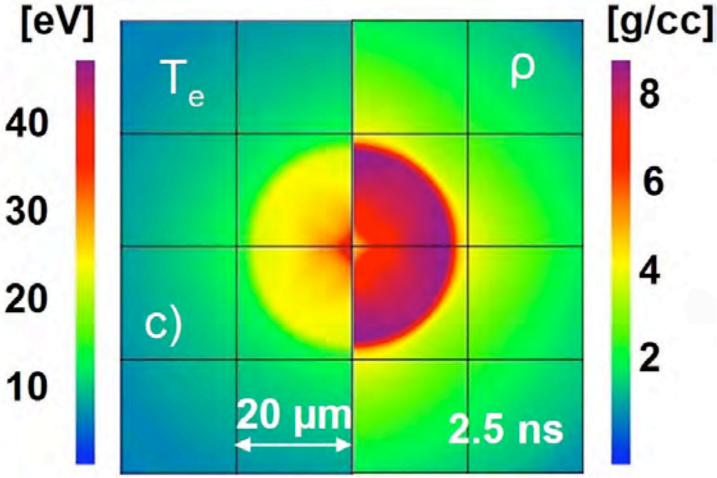


ρ_0 = 1g/cc



Density (right) and **temperature** (left) polar maps at the maximum compression

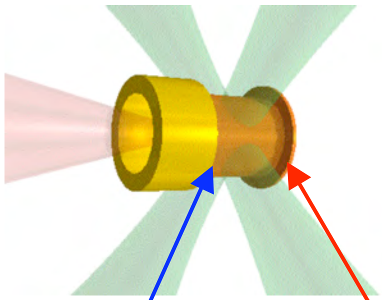


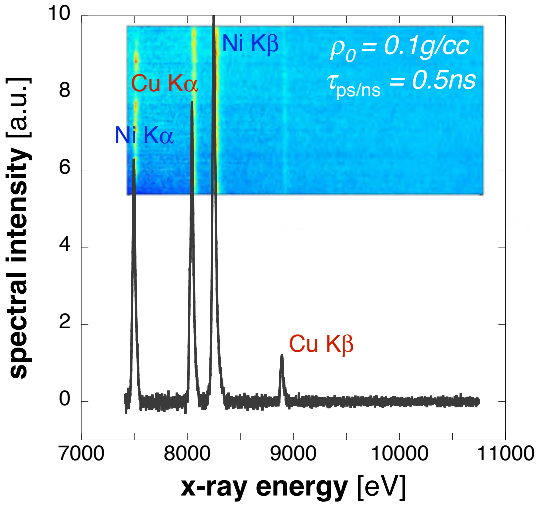


Cf. B. Vauzour *et al.*, to be submitted to Phys. Plasmas

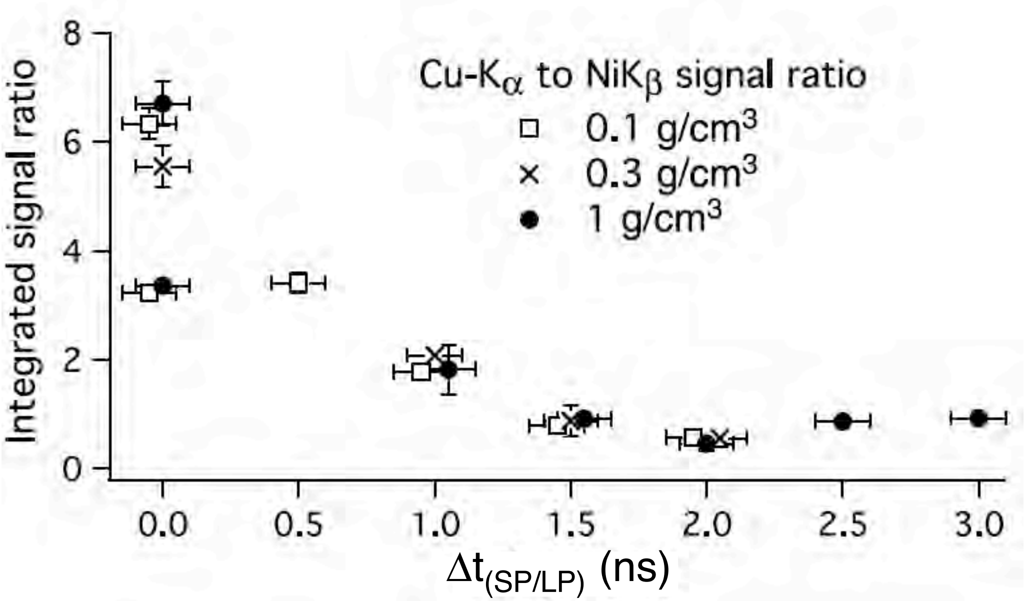
2D hydro simulations performed with the code CHIC, P.H. Maire *et al.*, SIAM J. Sci. Comput. **29**, 4 (2007)

Phase 2: Study of the fast electron transport
K-shell X-rays spectroscopy





- ✓ Kα and Kβ signals from Ni (electron source tracer) are relatively constant against the short pulse delay
  The electron source is supposed to be a fixed parameter
- ✓ **Correction of the shot-to-shot variations** of the fluorescence yield from Cu (rear side tracer):
  Cu-Kα yields are adjusted to the Ni-Kβ yields

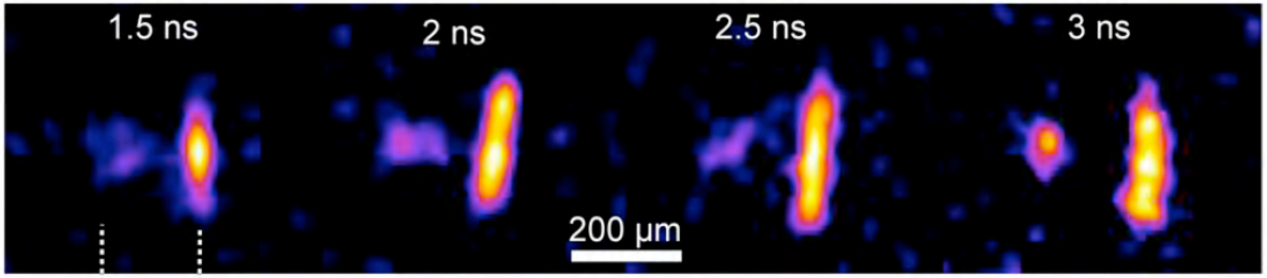


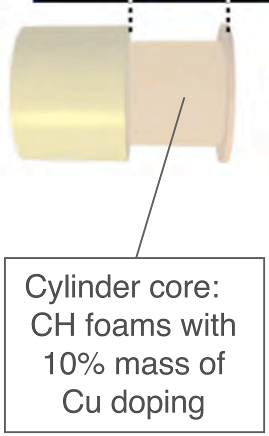
➡ **The fraction of electrons reaching the target rear surface decreases during compression $\forall \rho_0$**
(no clear dependence on the initial foam density)

Cf. F. Perez *et al.*, PPCF **51**, 124035 (2010)

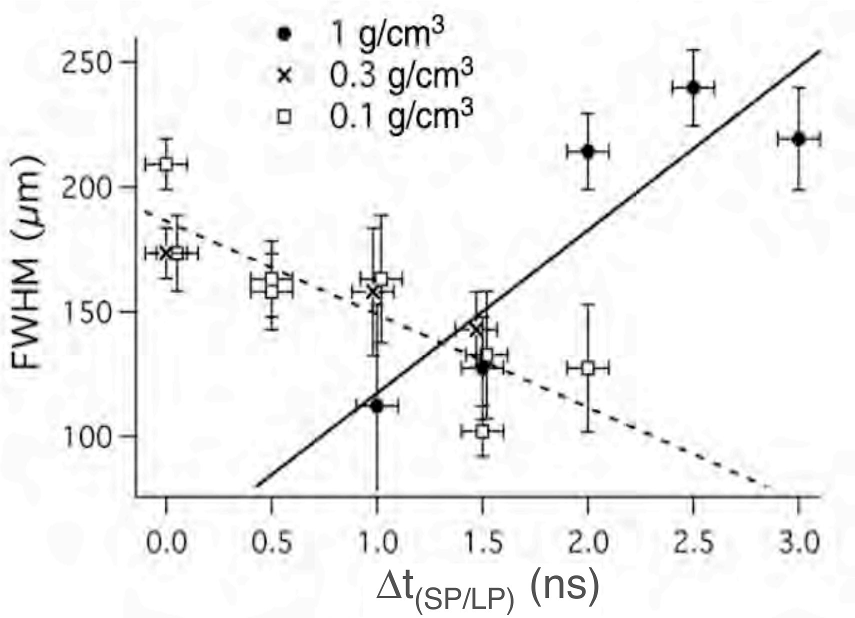
Phase 2: Study of the fast electron transport
K-shell X-rays imaging and spectroscopy

Sample images of Cu-Kα fluorescence from ρ_0 = 1g/cc targets





➡ **Fast electron propagation seen inside the compressed targets**



➡ **Size of the fast electrons beam measured at the rear side foil:**

- **ρ_0 = 1g/cc**
  compression makes the beam diverge
- **ρ_0 = 0.1g/cc**
  compression makes the beam converge

Cf. F. Perez *et al.*, PPCF **51**, 124035 (2010)

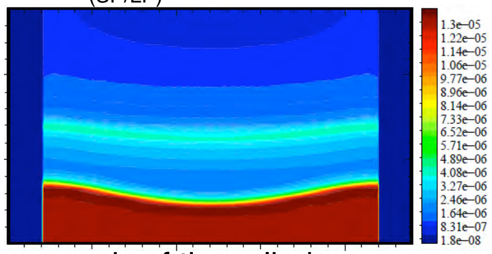
Non homogeneous resistivity affects the fast electron transport in compressed cylindrical plasmas

▪ Case of ρ_0=1g/cc at $\Delta t_{(SP/LP)}$=1.5ns

Before the full compression, the density is not perturbed at the center and the temperature is low.

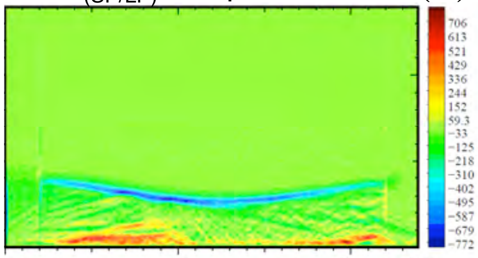
t = $\Delta t_{(SP/LP)}$ η (Ωm)

Intense laser direction

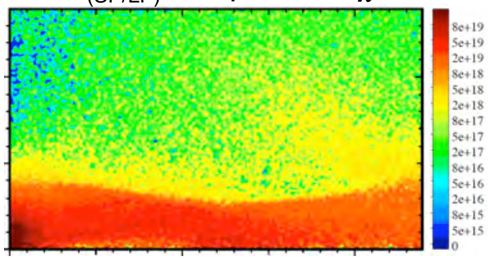


axis of the cylinder

t = $\Delta t_{(SP/LP)}$ + 10ps B (T)



t = $\Delta t_{(SP/LP)}$ + 10ps n_h (e^-/cc)



$$\frac{\partial_r \eta}{\eta} \gg \frac{\partial_r j_{hz}}{j_{hz}} \Rightarrow \partial_t B_\varphi \sim -j_{hz}\partial_r \eta$$

(Faraday's law)

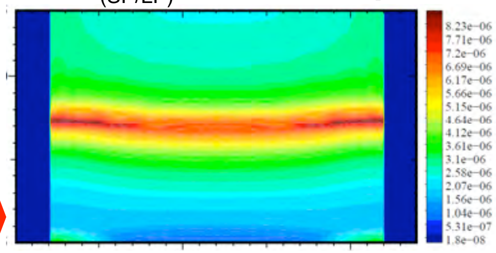
➡ A high resistivity channel produces a collimating magnetic field that focuses the electrons towards high resistivity regions

▪ Case of ρ_0=1g/cc at $\Delta t_{(SP/LP)}$=2ns

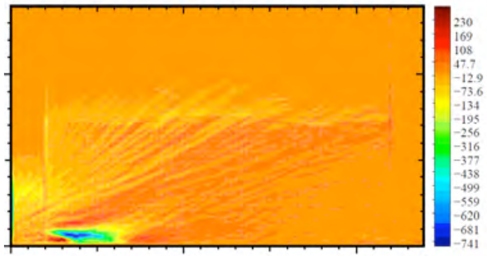
The shocks have already converged. Density is maximum at the center BUT also the temperature.

t = $\Delta t_{(SP/LP)}$ η (Ωm)

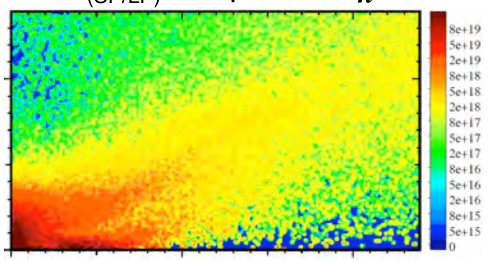
Intense laser direction



t = $\Delta t_{(SP/LP)}$ + 10ps B (T)



t = $\Delta t_{(SP/LP)}$ + 10ps n_h (e^-/cc)



➡ Low resistivity on the cylinder's axis. No resistive collimating magnetic field is present and the fast electron beam diverges.

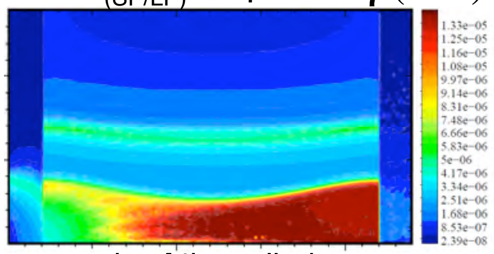
Courtesy of A. Debayle, J.J. Honrubia, F. Perez and R. Ramis

Non homogeneous resistivity affects the fast electron transport in compressed cylindrical plasmas

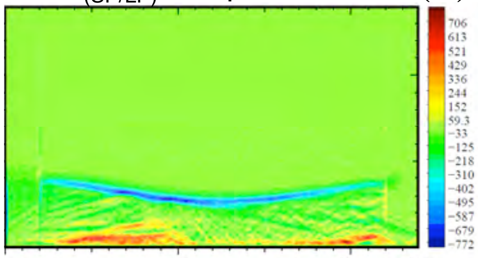
- **Case of ρ_0=1g/cc at $\Delta t_{(SP/LP)}$=1.5ns**

Before the full compression, the density is not perturbed at the center and the temperature is low.

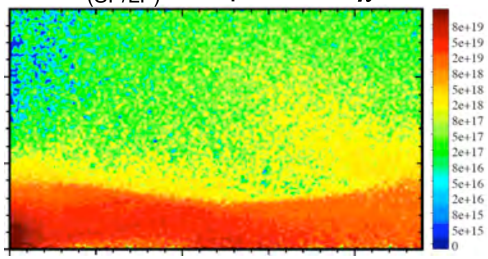
t = $\Delta t_{(SP/LP)}$ + 5ps η (Ωm)



t = $\Delta t_{(SP/LP)}$ + 10ps B (T)



t = $\Delta t_{(SP/LP)}$ + 10ps n_h (e$^-$/cc)



Intense laser direction

axis of the cylinder

$$\frac{\partial_r \eta}{\eta} \gg \frac{\partial_r j_{hz}}{j_{hz}} \Rightarrow \partial_t B_\varphi \sim -j_{hz}\partial_r \eta$$

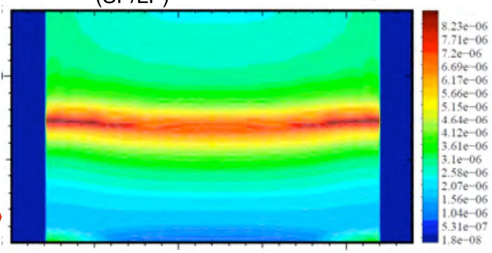
(Faraday's law)

➡ A high resistivity channel produces a collimating magnetic field that focuses the electrons towards high resistivity regions

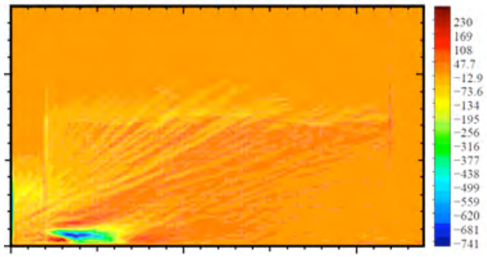
- **Case of ρ_0=1g/cc at $\Delta t_{(SP/LP)}$=2ns**

The shocks have already converged. Density is maximum at the center BUT also the temperature.

t = $\Delta t_{(SP/LP)}$ η (Ωm)



t = $\Delta t_{(SP/LP)}$ + 10ps B (T)



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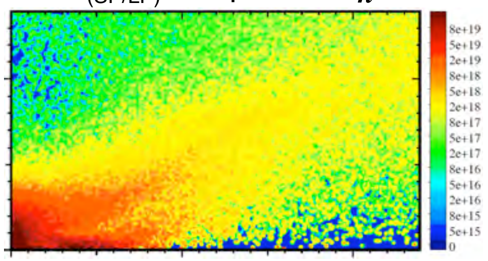

Intense laser direction

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Courtesy of A. Debayle, J.J. Honrubia, F. Perez and R. Ramis

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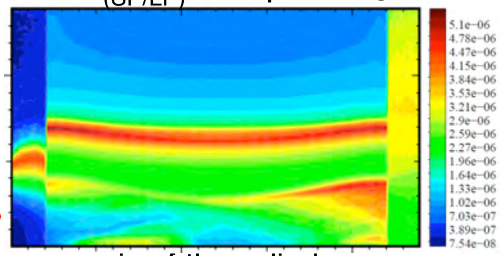
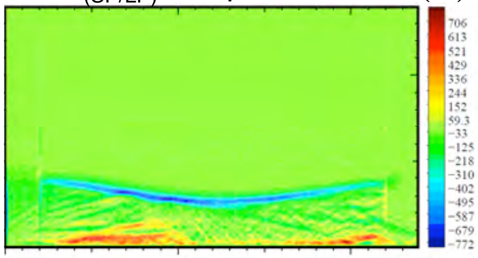
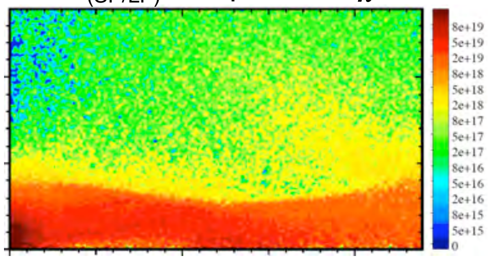


t = $\Delta t_{(SP/LP)}$ + 10ps $\boldsymbol{B}$ (T)



t = $\Delta t_{(SP/LP)}$ + 10ps $\boldsymbol{n_h}$ (e^-/cc)



Intense laser direction

axis of the cylinder

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(Faraday's law)

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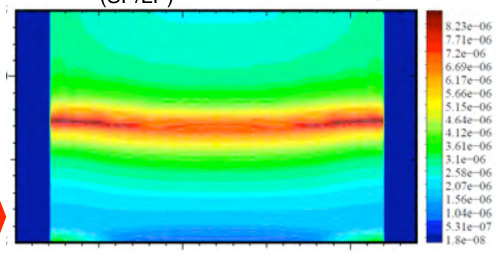
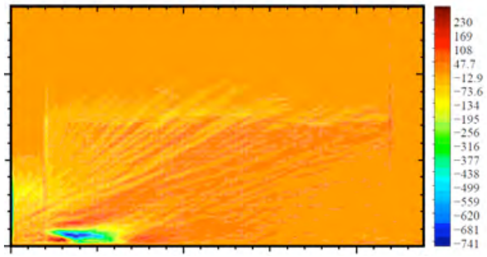
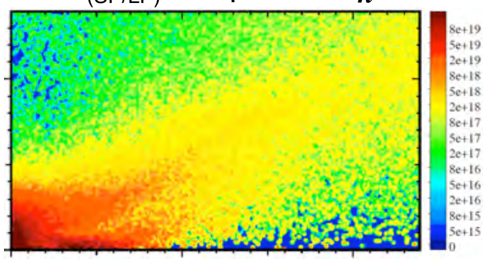


t = $\Delta t_{(SP/LP)}$ + 10ps $\boldsymbol{B}$ (T)



t = $\Delta t_{(SP/LP)}$ + 10ps $\boldsymbol{n_h}$ (e^-/cc)



Intense laser direction

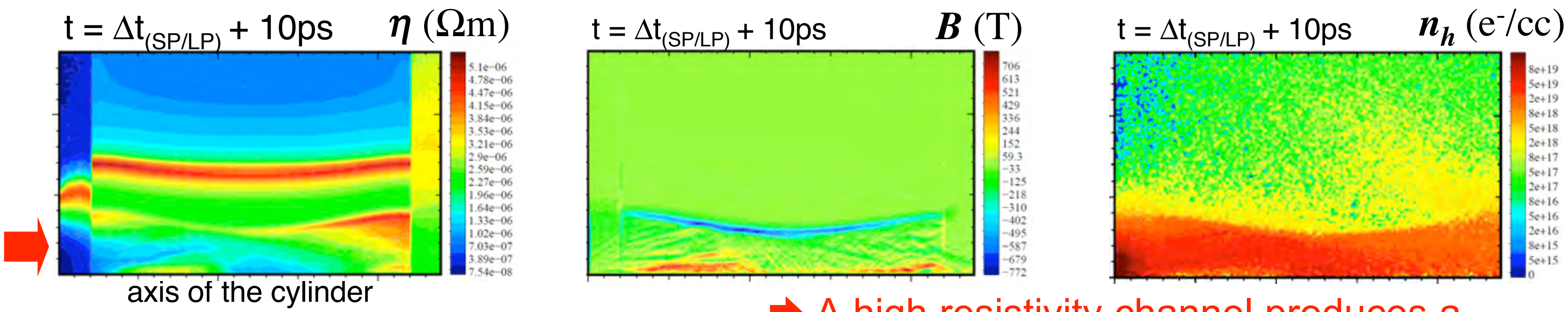
➡ Low resistivity on the cylinder's axis. No resistive collimating magnetic field is present and the fast electron beam diverges.

Courtesy of A. Debayle, J.J. Honrubia, F. Perez and R. Ramis

Non homogeneous resistivity affects the fast electron transport in compressed cylindrical plasmas

- Case of ρ_0=1g/cc at $\Delta t_{(SP/LP)}$=1.5ns

Before the full compression, the density is not perturbed at the center and the temperature is low.



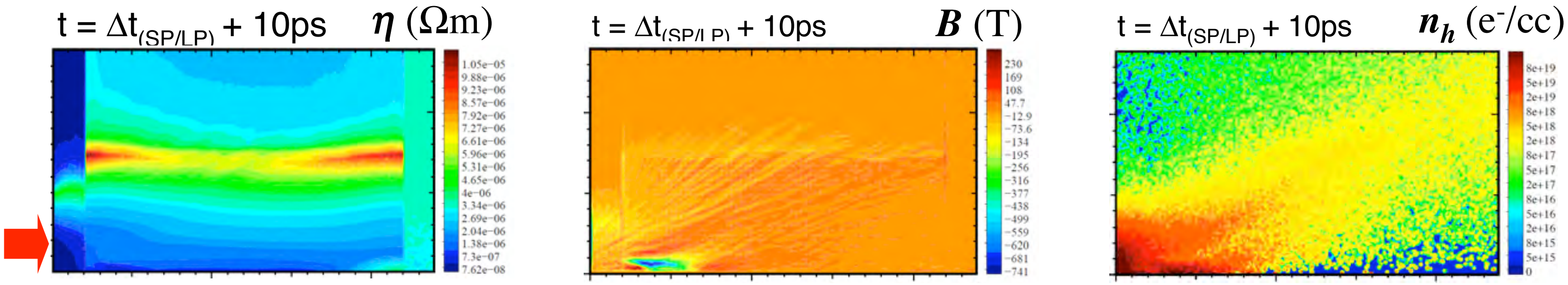
$$\frac{\partial_r \eta}{\eta} \gg \frac{\partial_r j_{hz}}{j_{hz}} \Rightarrow \partial_t B_\varphi \sim -j_{hz}\partial_r \eta$$

(Faraday's law)

➡ A high resistivity channel produces a collimating magnetic field that focuses the electrons towards high resistivity regions

- Case of ρ_0=1g/cc at $\Delta t_{(SP/LP)}$=2ns

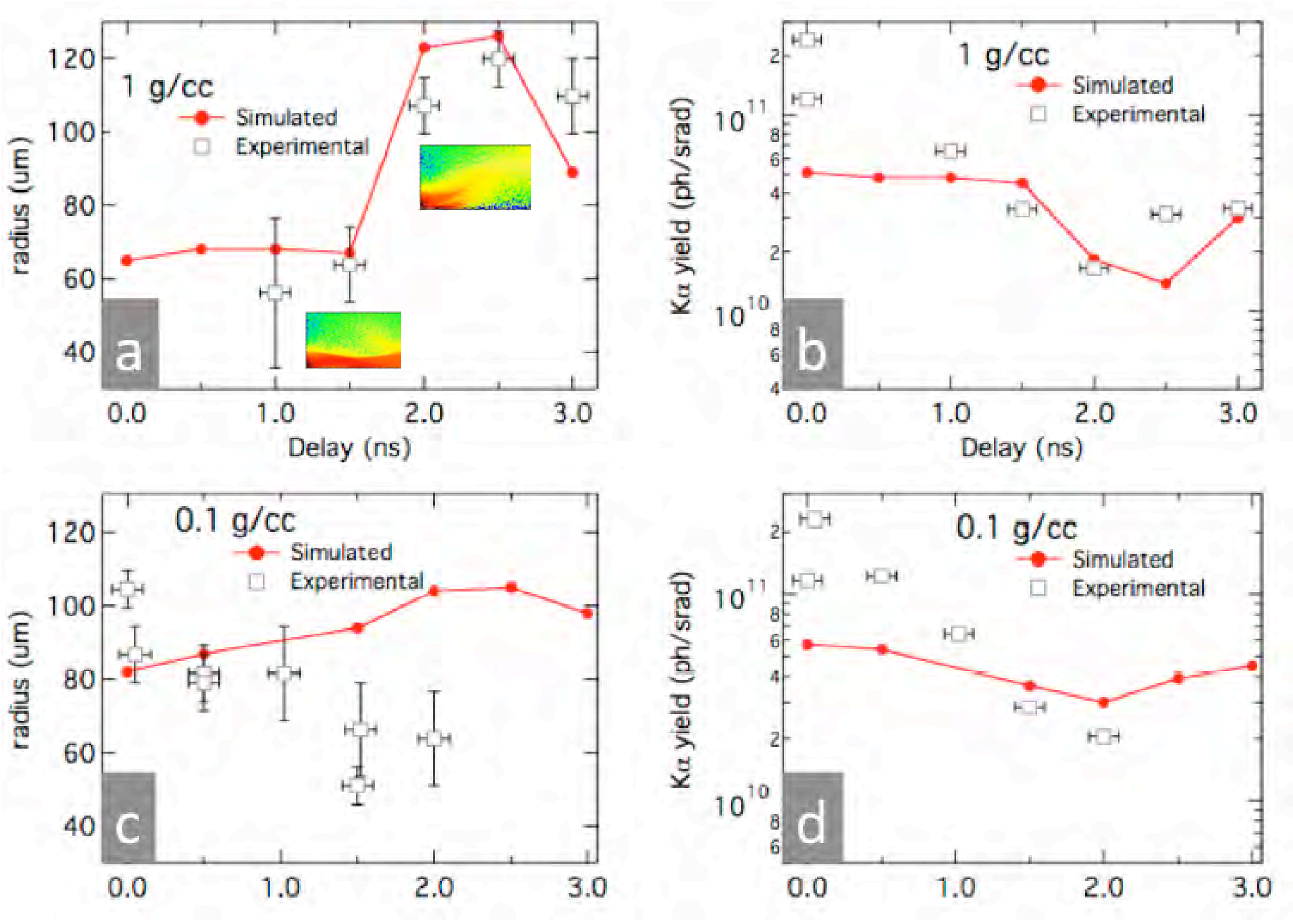
The shocks have already converged. Density is maximum at the center BUT also the temperature.



➡ Low resistivity on the cylinder's axis. No resistive collimating magnetic field is present and the fast electron beam diverges.

Courtesy of A. Debayle, J.J. Honrubia, F. Perez and R. Ramis

Final size of the electron beam and the number of electrons reaching the rear side: simulations vs. experimental data



- **ρ_0 = 1g/cc**

  Good agreement between simulations and experiment.

  The electron beam is guided for some plasma conditions.

- **ρ_0 = 0.1g/cc**

  Simulation results do not match the data, especially for the electron beam size.

Need to scan the electron source parameters or improve the resistivity description at low temperatures.

Courtesy of A. Debayle, J.J. Honrubia, F. Perez and R. Ramis

Conclusions

DT HiPER target

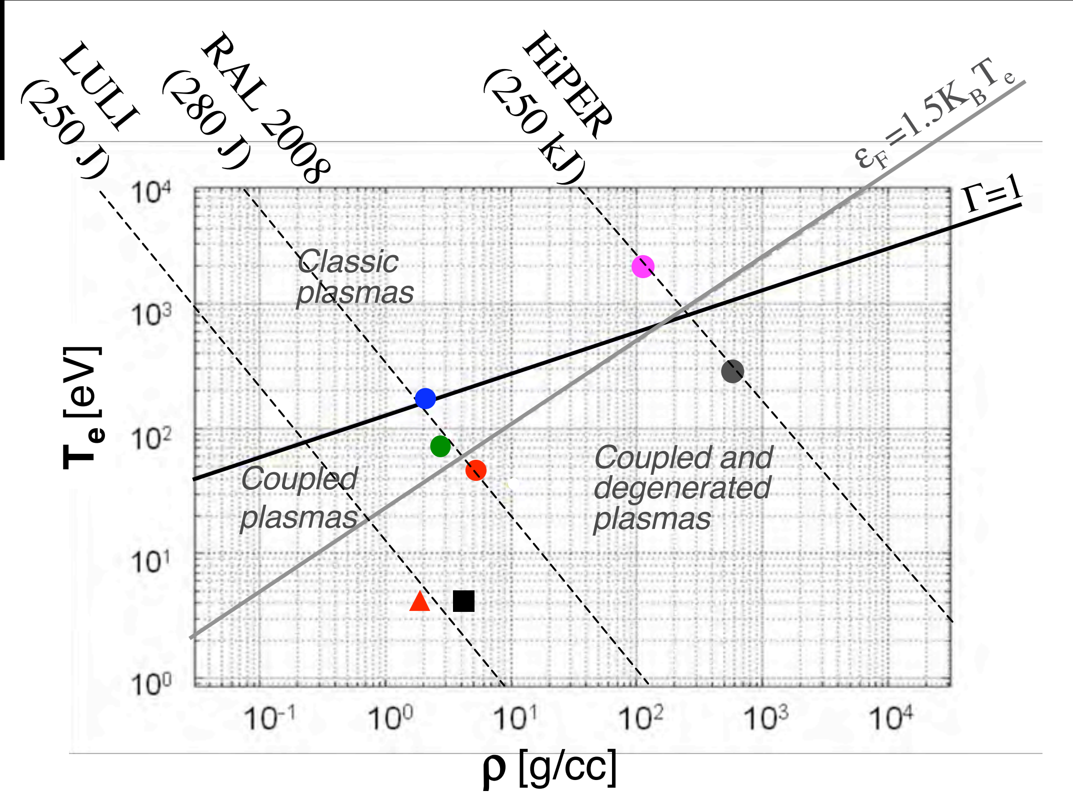
- ***hot spot*** — ρ = 80 g/cc, T = 2.5 keV
- ***dense fuel shell*** — ρ = 400 g/cc, T = 300 eV

RAL 2008 CH cylinders (on axis at stagnation)

- *ρ_0 = 0.1g/cc* — ρ = 2 g/cc, T = 125 eV
- *ρ_0 = 0.3g/cc* — ρ = 2.5 g/cc, T = 65 eV
- *ρ_0 = 1g/cc* — ρ = 5 g/cc, T = 45 eV

LULI 2008 and 2010 foil targets

- ***CH foil*** — ρ = 2 g/cc, T = 4 eV
- ***Al foil*** — ρ = 5 g/cc, T = 4 eV



➡ ***Tested experimental conditions offered the possibility to explore plasmas representative of:***
- ***the degeneracy of the compressed DT fuel***
- ***the ρ and T levels near the fast electron source***

Principal results:

➡ ***1D compression:*** *enhanced collective fast electron stopping power*

➡ ***2D compression:*** *many plasma parameters were tested and some cases produce an efficient collimation of the fast electron beam*

➡ ***Need to dimension higher compression factor-experiments at Omega EP, FIREX, PETAL, to test electron transport in different scenarii and progressively approach the real fast ignition conditions***