UNIVERSITÉ DE BORDEAUX

Current status of the laser fusion research and the shock ignition approach

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On behalf of the EUROFusion Enabling Research Project ENR-IFE19.CEA-01 “Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development ” and in particular *J.Trela, G.Boutoux, A.Casner, X.Ribeyre, V.Tikhonchuk, E.Le Bel, Ph.Nicolai, D.Raffestin, A.Colaitis, L.Antonelli, N.Woolsey, G.Cristoforetti, L.Gizzi, R.Scott, K.Glize, S.Pikuz, J.Honrubia, R.Florido, S.Atzeni, T.Pisarczyk, S.Guskov, D.Mancelli, A.Tentori, O.Renner, J.Dostal, R.Dudzak, M.Krus, F.Baffigi, E.Filippov, Y.J.Gu, O.Klimo, S.Malko, A.Martynenko, S.Pikuz, T.Chodukowski, Z.Kalinowska, M.Rosinski, …*

Experiments realised in collaboration with the University of Rochester team (Omega laser facility):
R.Betti, J.Peebles, W.Theobald, K.S.Anderson, J.A.Delettrez, V.Yu.Glebov, A.A.Solodov, M.Stoeckl, C. Stoeckl, M.Wei, Univ. Rochester, USA
J.A.Frenje, Massachusetts Institute of Technology, Cambridge MA, USA

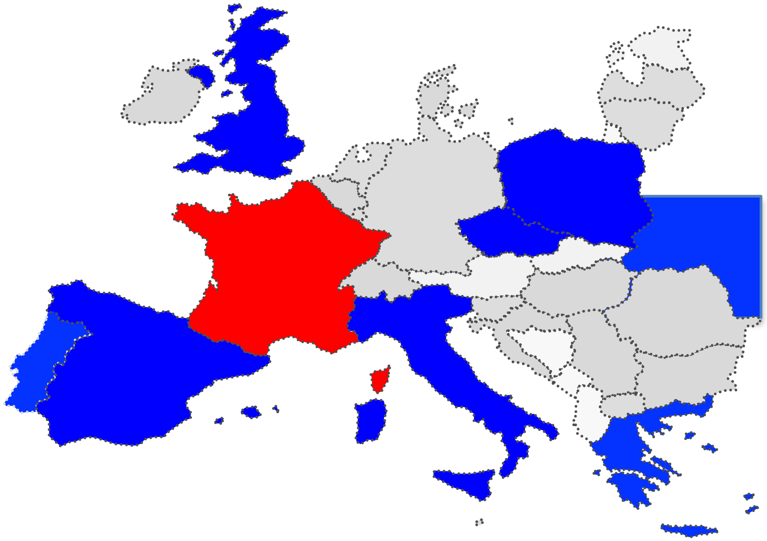
SPIG 2020

30th Summer School and International Symposium on the Physics of Ionized Gases

August 24 - 28, 2020, Šabac, Serbia

EUROfusion *Support from Enabling Research Projects*

1) **CELIA, Bordeaux -** Group Leader: Dimitri Batani
2) **Prague team (IoP, ELI, PALS, CTU Prague) -** Group Leader: Miroslav Krous
3) **University of Rome "La Sapienza" -** Group Leader: Stefano Atzeni
4) **UK shock ignition collaboration (Univ. York, Warwick, Strathclyde, STFC) -** Group Leader: Nigel Woolsey
5) **Universidad de Las Palmas de Gran Canaria (ULPGC) -** Group Leader: Ricardo Florido
6) **IPPLM, Warsaw -** Group Leader: Tadeusz Pisarczyk
7) **INO, CNR, Pisa Italy -** Group Leader: Gabriele Cristoforetti
8) **Polytechnic University of Madrid, Spain -** Group Leader: Javier Honrubia
9) **CLPU, Salamanca, Spain -** Group Leader: Luca Volpe
10) **ENEA, Frascati, Italy -** Group Leader: Fabrizio Consoli
11) **IST, Lisbon, Portugal -** Group Leader: Marta Fajardo
12) **LULI, Palaiseau, France -** Group Leader: Sophie Baton
13) **CPPL of TEI of Crete, Greece -** Group Leader: Michael Tatarakis
14) **Kharkov Institute of Physics & Technology, Ukraine -** Group Leader: Vasyl Maslov
15) **Università di Milano Bicocca, Italy -** Group Leader: Giuseppe Gorini



ENR-IFE19-CEA-01 **Study of Direct Drive and Shock Ignition for IFE: Theory, Simulations, Experiments, Diagnostics development**

Participants: FR, CZ, ES, IT, PL, UK, GR, PT, UKR

Summary

1) What is shock ignition

2) The problem of hot electrons and Experiments at PALS and Omega-EP

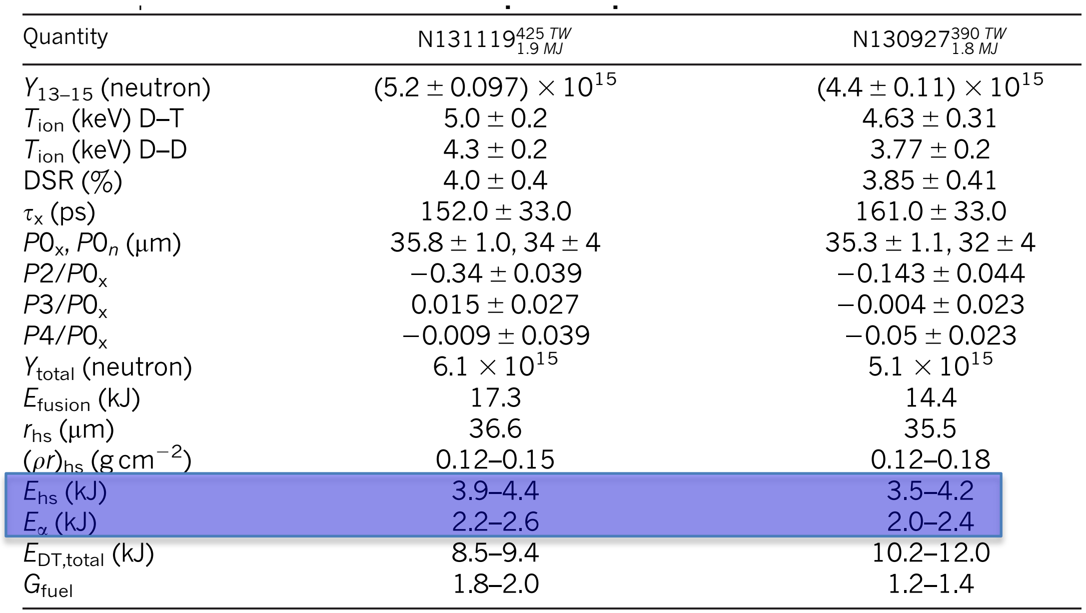
3) Roadmap to shock ignition

(many other experiments in several other facilities:

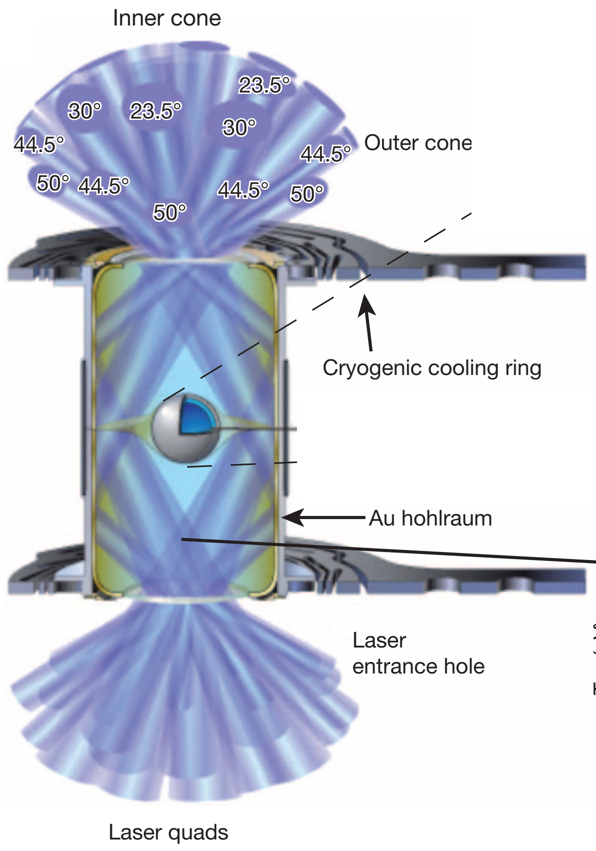
LIL, LULI, Phelix... Gekko...)

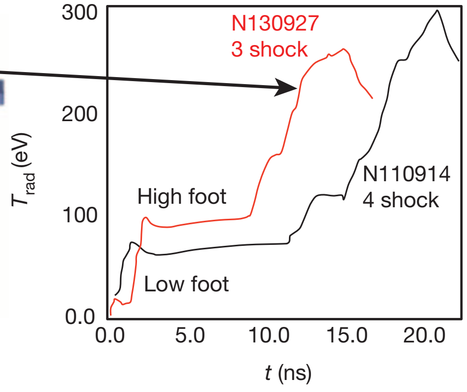
NIF:nteresting results after

High-foot implosions (O.Hurricane, et al. Nature 2014) have allowed entering a novel “α-heating regime”



Quantity	$\mathrm{N131119}^{425\,TW}_{1.9\,MJ}$	$\mathrm{N130927}^{390\,TW}_{1.8\,MJ}$
$Y_{13\text{–}15}$ (neutron)	$(5.2 \pm 0.097) \times 10^{15}$	$(4.4 \pm 0.11) \times 10^{15}$
T_{ion} (keV) D–T	5.0 ± 0.2	4.63 ± 0.31
T_{ion} (keV) D–D	4.3 ± 0.2	3.77 ± 0.2
DSR (%)	4.0 ± 0.4	3.85 ± 0.41
τ_x (ps)	152.0 ± 33.0	161.0 ± 33.0
$P0_x$, $P0_n$ (μm)	35.8 ± 1.0, 34 ± 4	35.3 ± 1.1, 32 ± 4
$P2/P0_x$	-0.34 ± 0.039	-0.143 ± 0.044
$P3/P0_x$	0.015 ± 0.027	-0.004 ± 0.023
$P4/P0_x$	-0.009 ± 0.039	-0.05 ± 0.023
Y_{total} (neutron)	6.1×10^{15}	5.1×10^{15}
E_{fusion} (kJ)	17.3	14.4
r_{hs} (μm)	36.6	35.5
$(\rho r)_{\text{hs}}$ ($\mathrm{g\,cm^{-2}}$)	0.12–0.15	0.12–0.18
E_{hs} (kJ)	3.9–4.4	3.5–4.2
E_{α} (kJ)	2.2–2.6	2.0–2.4
$E_{\text{DT,total}}$ (kJ)	8.5–9.4	10.2–12.0
G_{fuel}	1.8–2.0	1.2–1.4

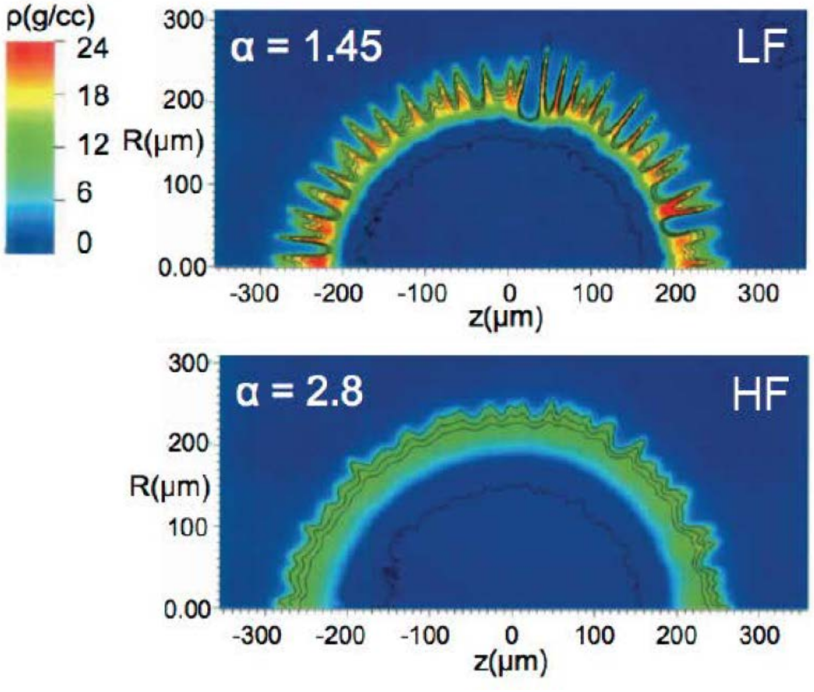




This also shows that the MAIN problem towards ignition is REALLY the impact of hydro instabilities related to non-uniformities

The best NIF implosions used the High-Foot laser pulse that drives stronger shocks in the "foot"

O. Hurricane, APS DPP meeting (2013)



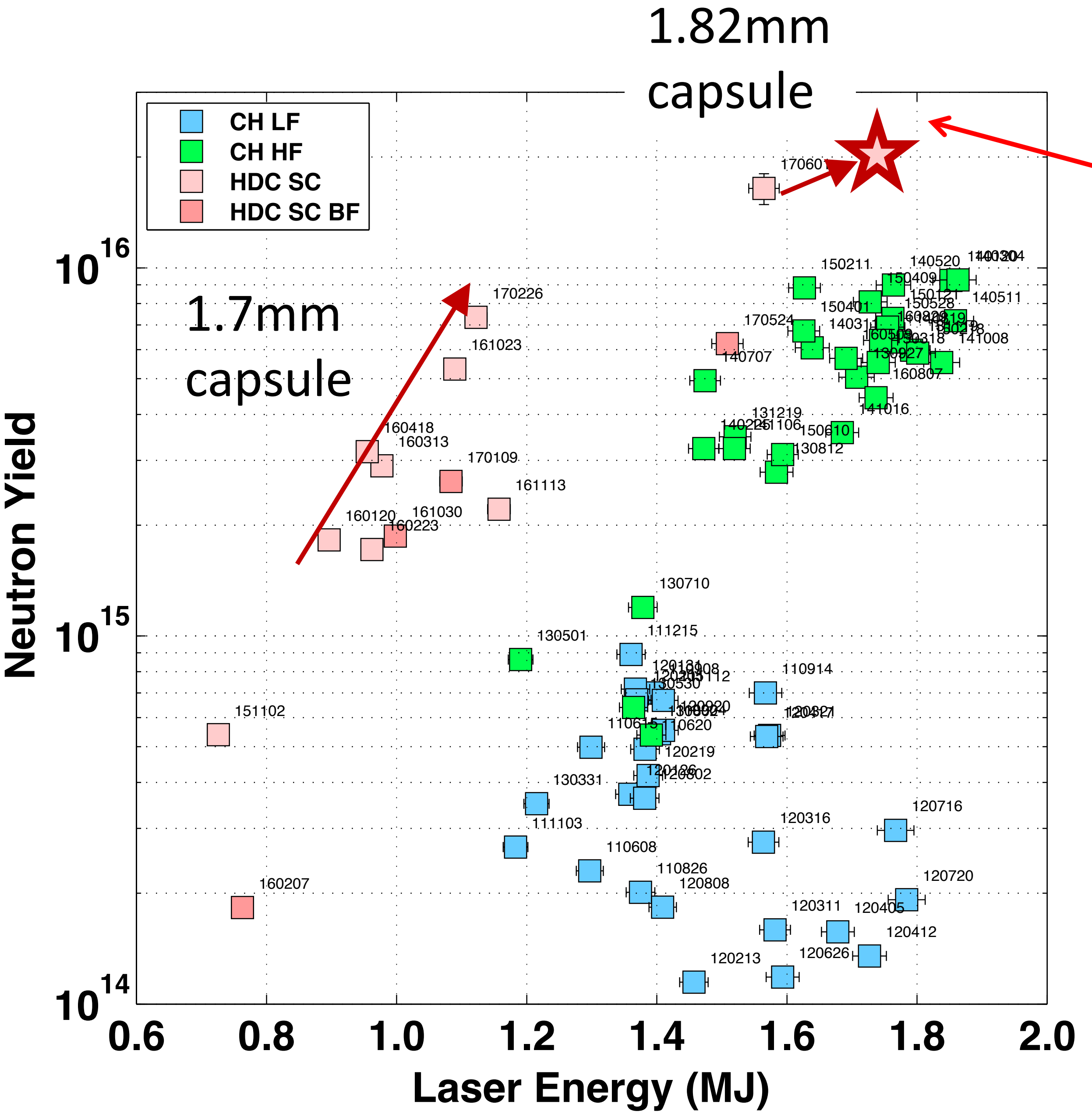
The high foot pulse set the imploding shell on a higher isentrope α (nothing to do with α-particles) because it launches stronger shocks in the "foot" of the pulse

$$\gamma = \sqrt{\frac{Akg}{1+kL}} - \beta k v_{abl}$$

Increase with α

High-foot growth-factor calculations and simulations are consistent with the expectation of less instability

Very recent results on NIF



W-doped HDC capsule driven in a low-gas-fill hohlraum 390 km/s, 2e16, 57 kJ of fusion yield, more than 2x α-heating

Near Vacuum Hohlraums reduce Laser-Plasma-Instabilities

HDC (diamond) or Beryllium Ablator have greater hydrodynamic efficiency allowing a more massive (and more stable) shell to be imploded

Rugby holhraum

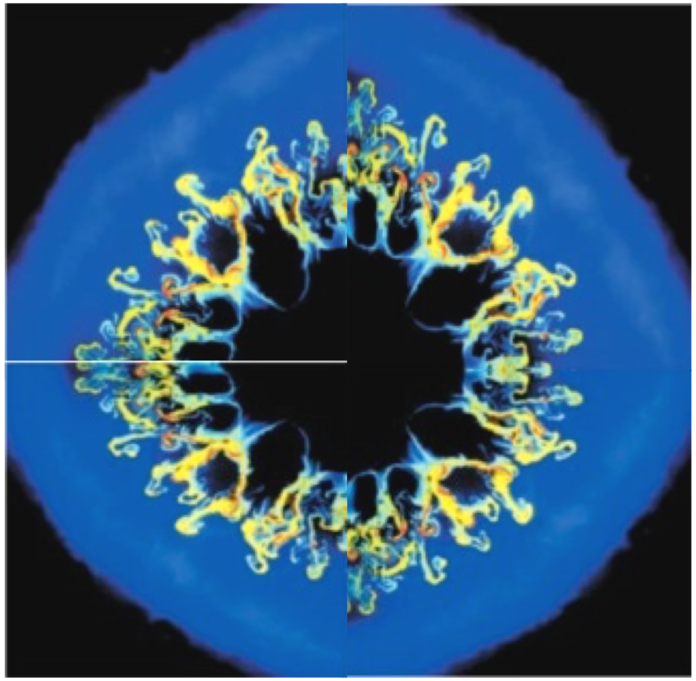
Direct Drive ICF

1) The impact of hydrodynamic instabilities (Rayleigh-Taylor) is the main obstacle to achieving ignition in indirect-drive inertial confinement fusion experiments

2) For future reactors we need DIRECT DRIVE:

- Higher gains
- Smaller laser facilities
- Simpler targets and simpler scheme more compatible with high-repetition rate operation and requirements of fusion reactors

Unfortunately Direct Drive is even more prone to uniformity problems and hydro-instabilities



Possible Solution:

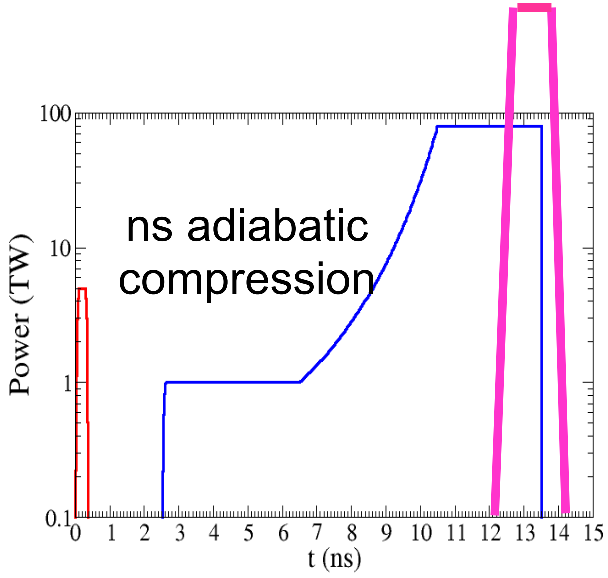
Decoupling compression and ignition phases

→ Fast Ignition
→ Shock Ignition

Shock Ignition

- Scheme proposed by R. Betti, J.Perkins et al. [PRL 98 (2007)] and anticipated by V. A. Shcherbakov [Sov.J. Plasma Phys. 9, 240 (1983)]

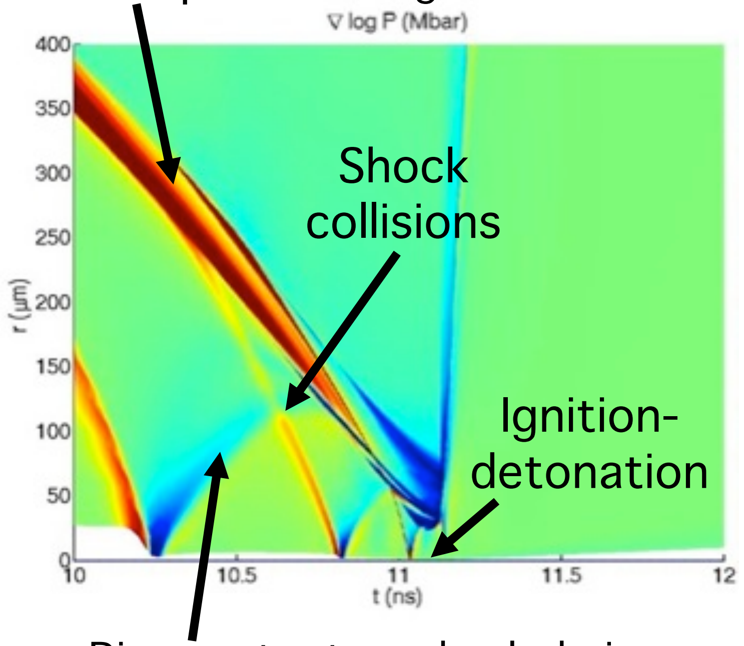
- Thicker and more massive target
  Lower implosion velocity V ≈ 240 km/s



ns adiabatic compression

Ignition spike (a few 100 ps)

Shock spike convergence



Shock collisions

Ignition-detonation

Divergent return shock during the shell stagnation phase

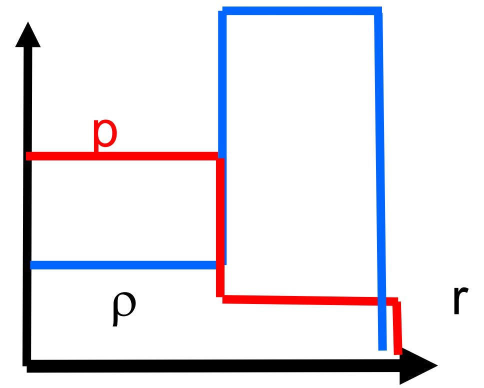
- A final laser spike launches a converging shock: at least 300 Mbar at the ablation front)

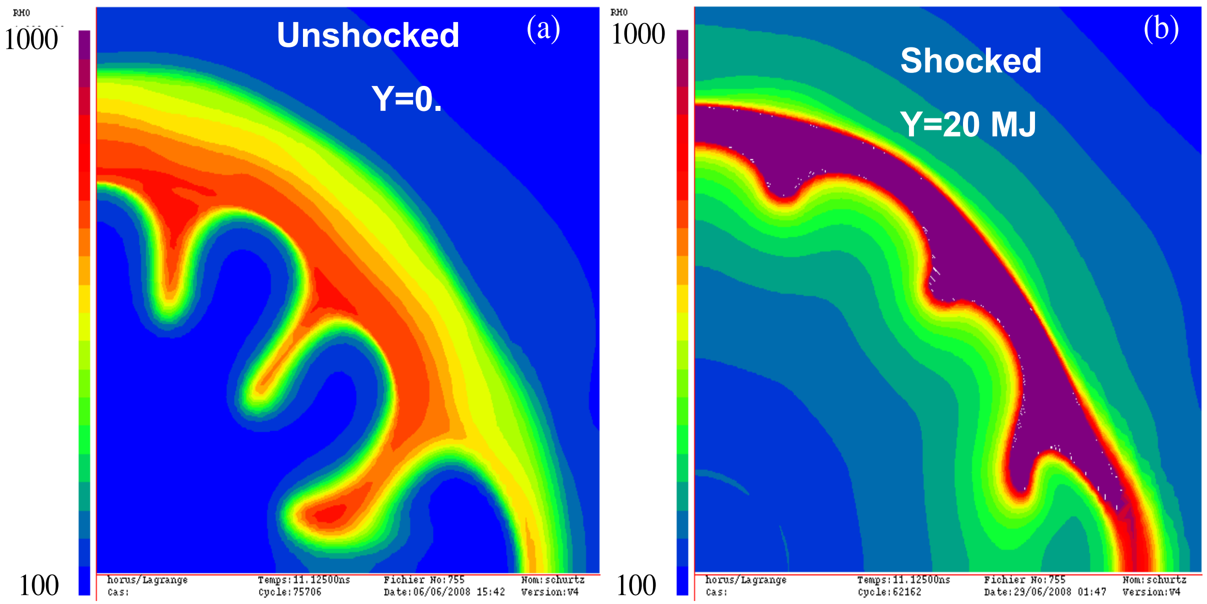
- The ignition shock collides with the return shock and provides the necessary amount of energy to trigger ignition from the central hot spot

Advantages of Shock Ignition

1) Since compression phase does not provide a central hot spot, we can implode a thicker target at lower velocity, much less sensitive to hydro instabilities

2) Non isobaric fuel assembly implies higher gains





Simulations by S.Atzeni

In addition RT growth can also be mitigated due to competition between Rayleigh-Taylor and Ritchmayer-Meskhov

Shock ignition is compatible with present-day laser technology ☺

Unknowns of Shock Ignition

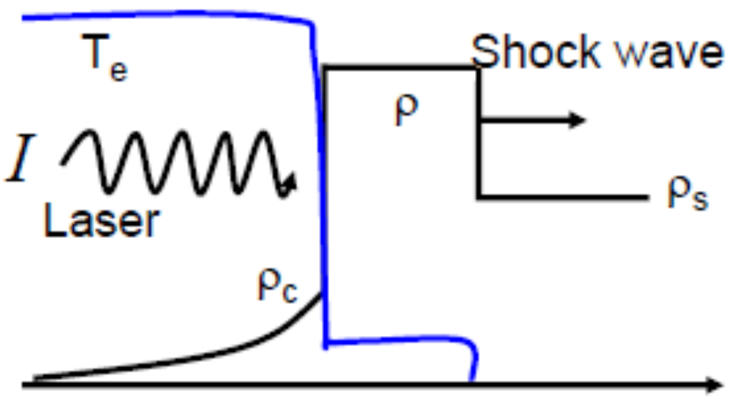
- Effect of laser-plasma instabilities at intensities up to ≈ 10^{16} W/cm^2. SRS, SBS and TPD. How they develop? How much light do they reflect?

- Are there many hot electrons and at what energy? What is their effect? *(usually in ICF hot electrons are dangerous since they preheat the target... Here they came at late times, large fuel* ρr*, so they could indeed be not harmful or even beneficial, increasing laser-target coupling in presence of a very extended plasma corona...)*

For more information:
D. Batani, S. Baton, A. Casner, S. Depierreux,M. Hohenberger, O. Klimo, M. Koenig, C. Labaune, X. Ribeyre, C. Rousseaux, G. Schurtz, W. Theobald, V. T. Tikhonchuk «Physical issues in shock ignition» Nuclear Fusion, **54** (2014) 054009

Difference between classical ablation pressure and hot electron driven pressure

isothermal corona: laser ablation



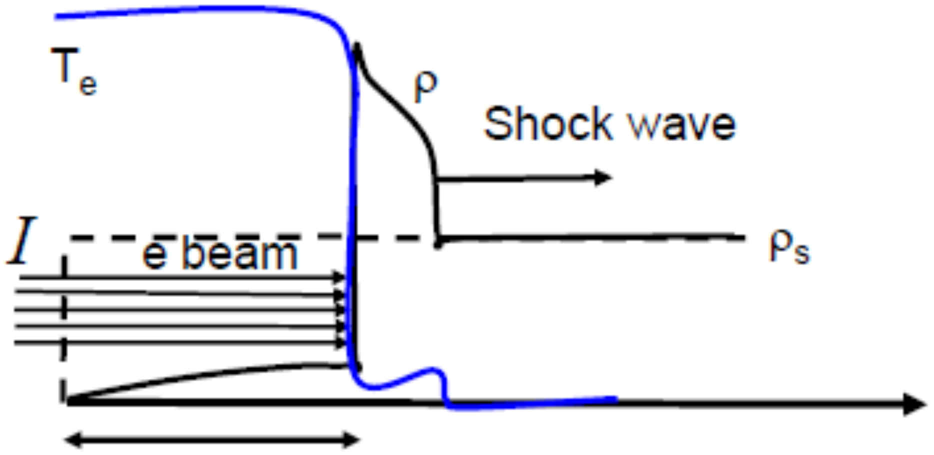
$$I = 4\rho_c C_s^3 \qquad C_s \propto T_e^{1/2}$$

$$P \propto \rho_c C_s^2 \qquad T_e \propto \left(\frac{I}{\rho_c}\right)^{2/3}$$

$$P \propto I^{2/3} \rho_c^{1/3}$$

ρ_c Critical density
(0.03 g/cc at 0.35 μm)

isothermal corona: hot electron ablation



$\lambda_p = \chi_{he} / \rho_s$ Hot electron stoping lenght

Time to estabilsh pressure

$$t_s \propto \frac{\chi_{he}}{I^{1/3} \rho_s^{2/3}}$$

$$P \propto I^{2/3} \rho_s^{1/3}$$

ρ_s Solid density
(10 g/cc for SI DT)

S. Guskov, et al. “Ablation Pressure Driven by an Energetic Electron Beam in a Dense Plasma” PRL 109, 255004 (2012)

Summary

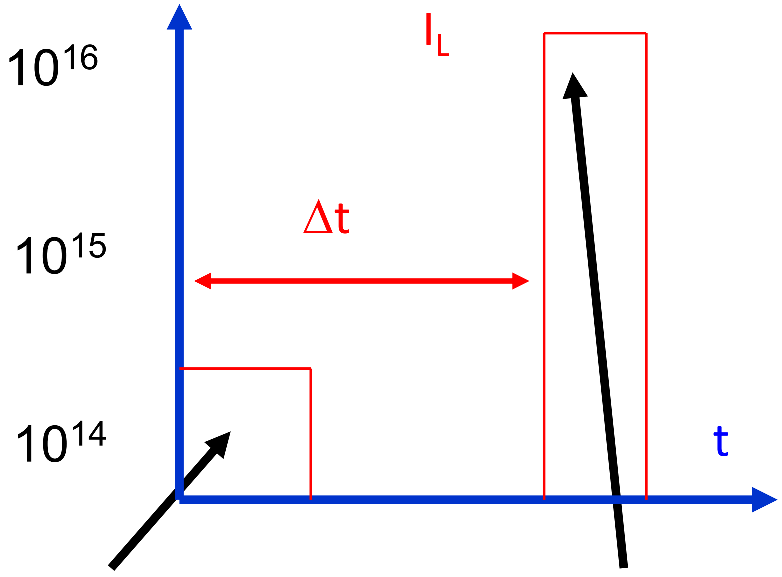
1) What is shock ignition

2) The problem of hot electrons and Experiments at PALS

3) Roadmap to shock ignition

Experiments at PALS - Prague

The PALS Iodine Laser
λ =1.3 μm τ = 300 ps E = 1500 J
3ω λ =0.44 μm E ≤ 500 J



Pre pulse 1ω

≤ 10^{14} W/cm^2
produces 1 keV
plasma

Drive 3ω or 1ω

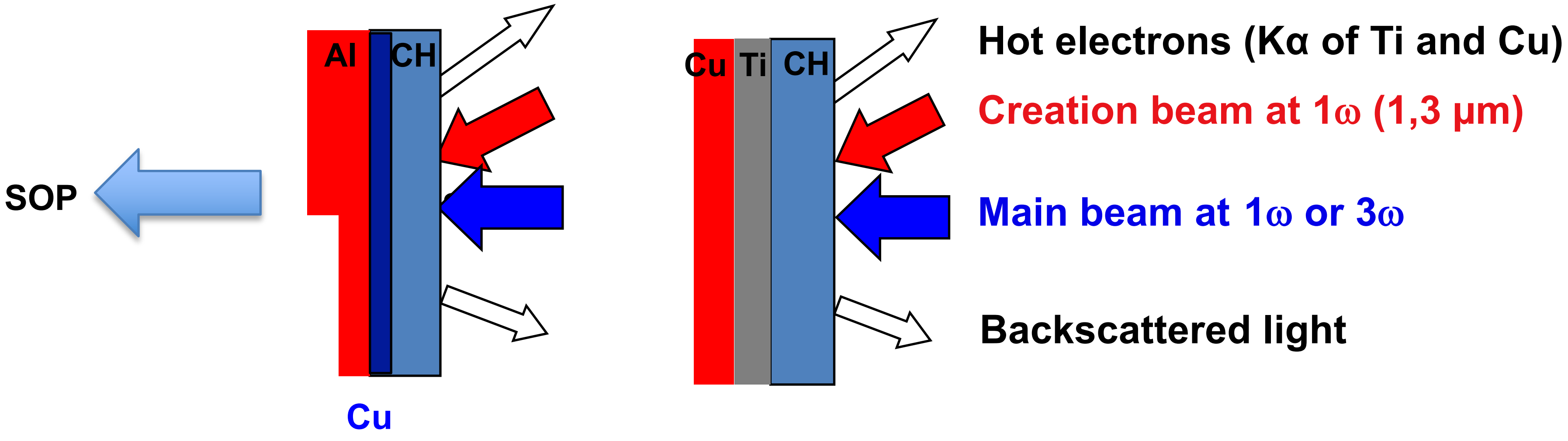
10^{16} W/cm^2

Launches a
strong shock

D. Batani, L. Antonelli, V. Tikhonchuk, J. Badziak, K. Jakubowska, Z. Kalinowska, T. Pisarczyk, M. Rosinski, G. Cristoforetti, P. Koester, L.A. Gizzi, S. Atzeni, A. Schiavi, M. Skoric, S. Gus'kov, J. Honrubia, J. Limpouch, O. Klimo, O. Renner, M. Krus, J. Ullschmied et al. "Progress in understanding the role of hot electrons for the shock ignition approach to inertial confinement fusion" Nucl. Fusion 59 (2019) 032012

Laser-Plasma Coupling in the Shock-Ignition Intensity Regime

- one beam to create the plasma : 1ω, 300 ps - 50J, I ~ 10^{14} W/cm^2, RPP Ø 300 µm
- one beam to launch the shock : 1ω or 3ω, 300 ps - 500 J, I ~ 10^{16} W/cm^2, Ø 100 µm


Shock target

Hot electron target

The CH layer simulates the low-Z material of the shell of a pellet.

The Al layer is a standard material for shock measurements

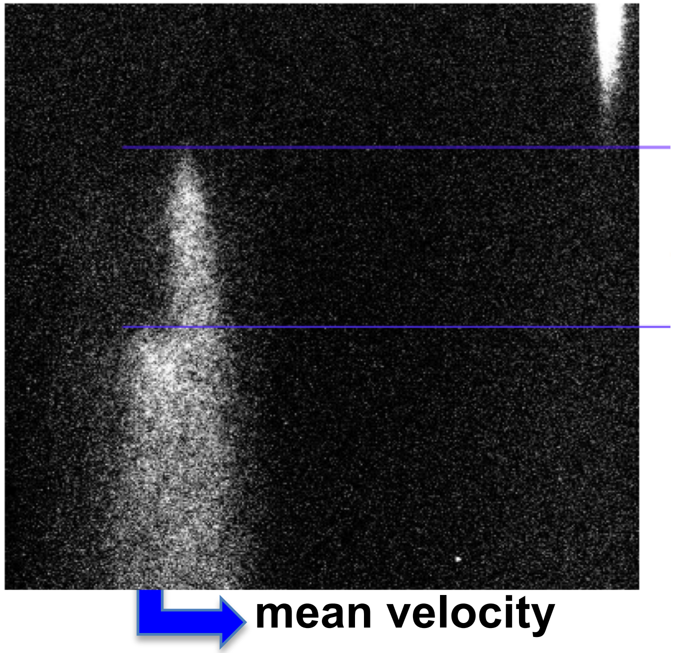
Cu and Ti used as tracer layer for Kα emission

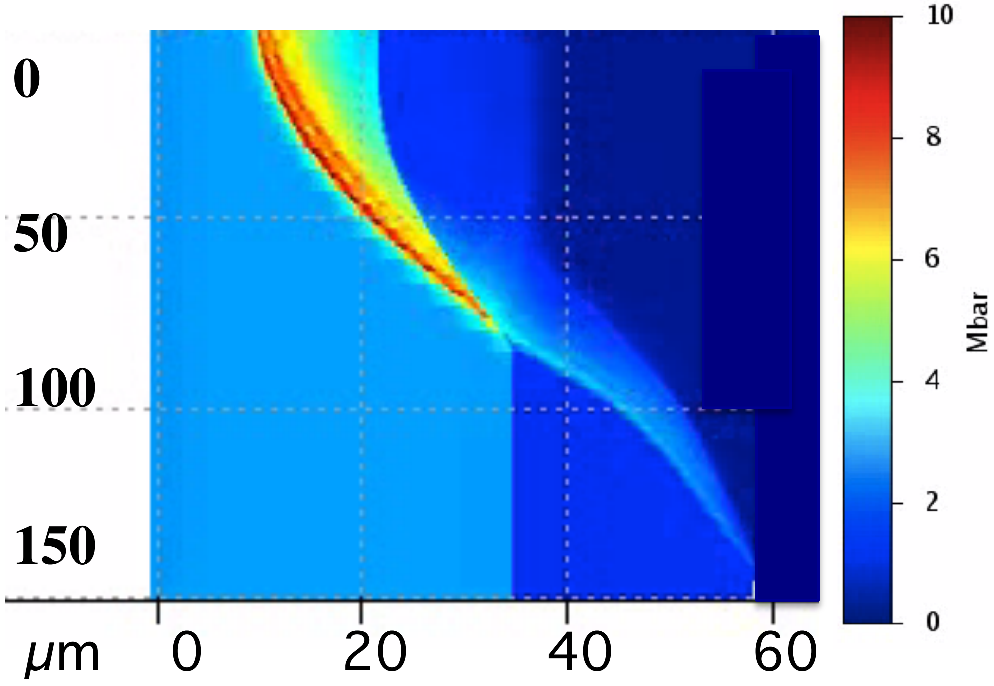
Shock chronometry for estimating the pressure (PALS)

Measured P at rear side much lower than ablation pressure at front side:
Shock pressure undergoes a rapid decrease due to:

1) 2D effects during propagation
2) Relaxation waves from front side when laser turns off

Target
25 μm CH
35 μm Al

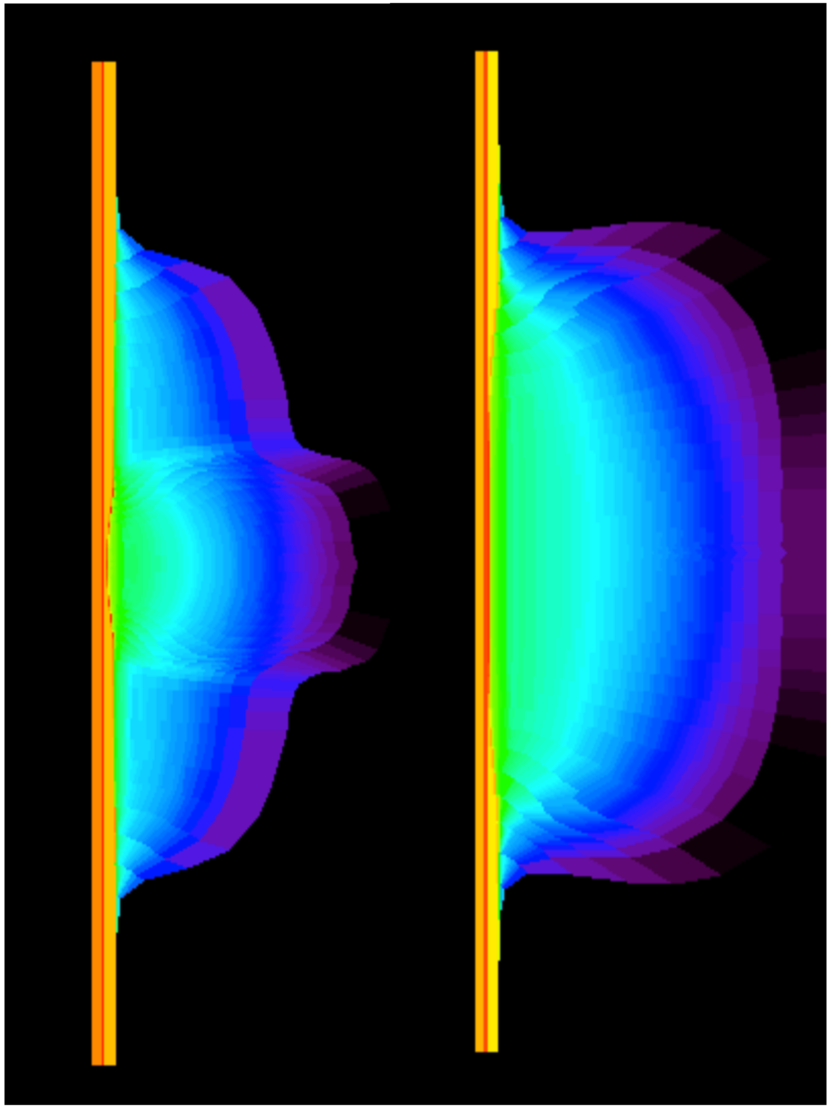




We run hydro simulations to match shock breakout time and we find that a final pressure ≤ 10 Mbar corresponds to a maximum **P ≈ 90 Mbar** during interaction.

2D Hydro simulations

Initial ablation pressure ≈ 90 Mbar << estimation from scaling laws



Explanations ?

***Lateral heat transport* in the *overdense region* is important and reduces the shock pressure**
(In our experiment spot size comparable to the distance between critical layer and ablation surface ≈40 μm vs. ≈100 μm)

Simulations with the same laser parameters but larger spot (≥ 400 μm) yield pressure ≈ 180 Mbar

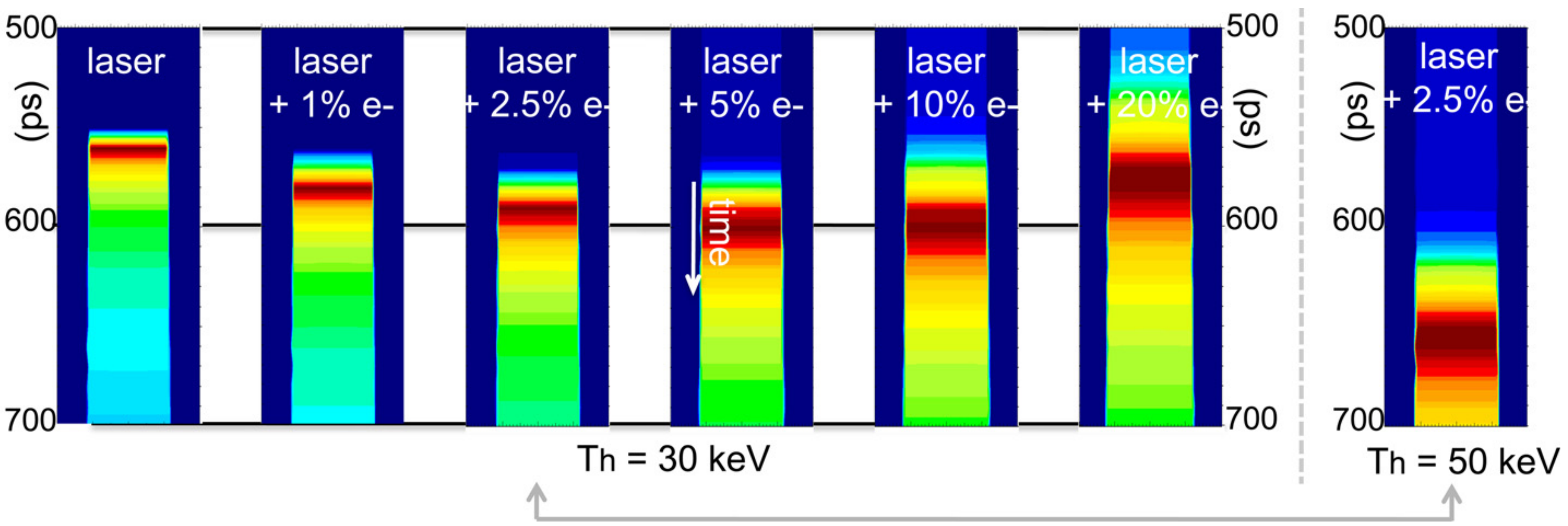
Still simulations reproduce well the trend of data but cannot retrieve the expected pressure at 10^{16} W/cm^2 (300 Mbar and not 180 !)

What did we forget?

Hot electrons may preheat the target material and induce a “preheat pressure” P*.
This results in:

- Decrease of compression
- Increase of shock velocity (early shock breakout)
- Expansion of target rear side (delayed shock breakout)

$$\rho^* = \rho_0 \frac{(\gamma+1)P^* + (\gamma-1)P_0}{(\gamma+1)P_0 + (\gamma-1)P^*}. \qquad D_s = \sqrt{\frac{(\gamma+1)P^* + (\gamma-1)P_0}{2\rho_0}}.$$



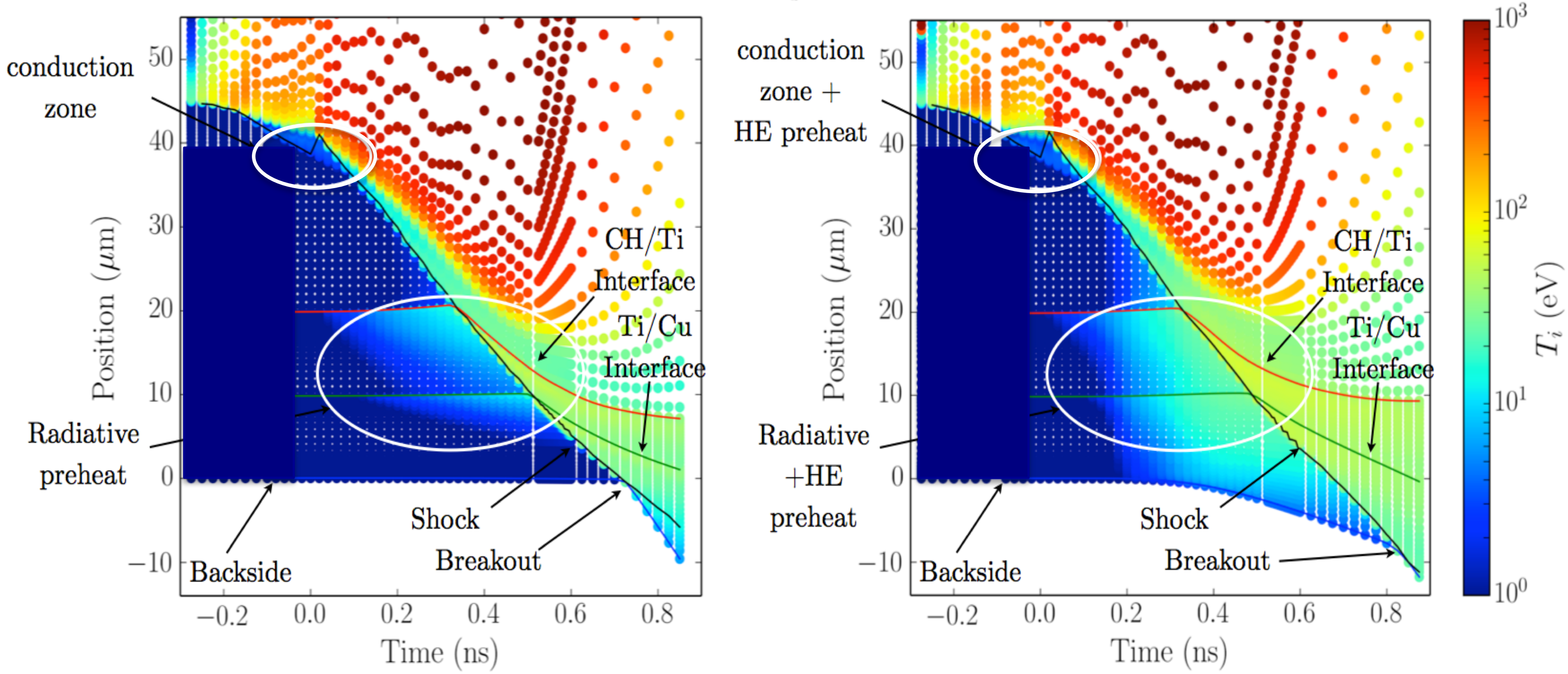
“Effect of nonthermal electrons on the shock formation in a laser driven plasma” Ph.Nicolaï et al. Phys. Plasmas, 22, 042705 (2015)

Simulations with “improved” model

“IMPROVED” HYDRO SIMULATION CODES:

- Better description of absorption (PCGO: from ray tracing to gaussian beamlets)
- Real time treatment of parametric instabilities and resonant absorption
- Generation of hot electrons and coupling to hydro (simplified kinetic transport)

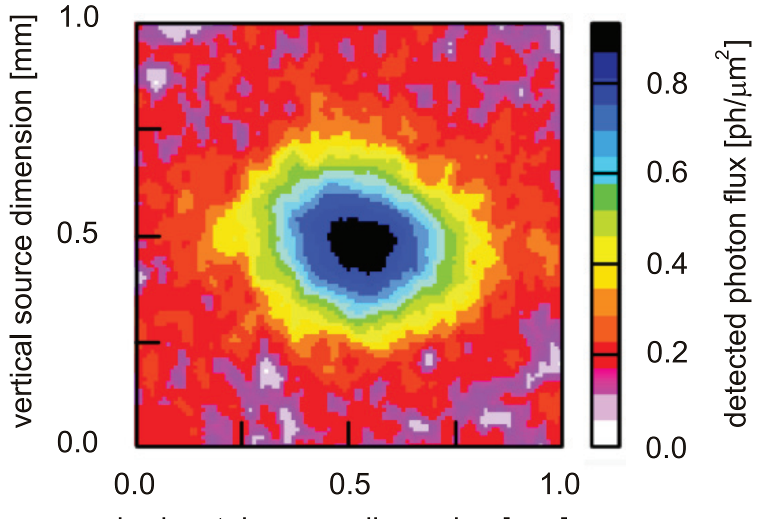
CH/Ti/Cu target **Without hot electrons** **With hot electrons**

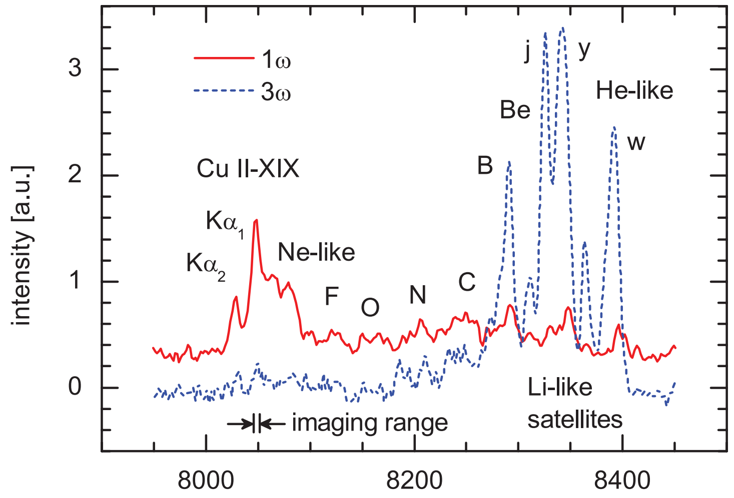


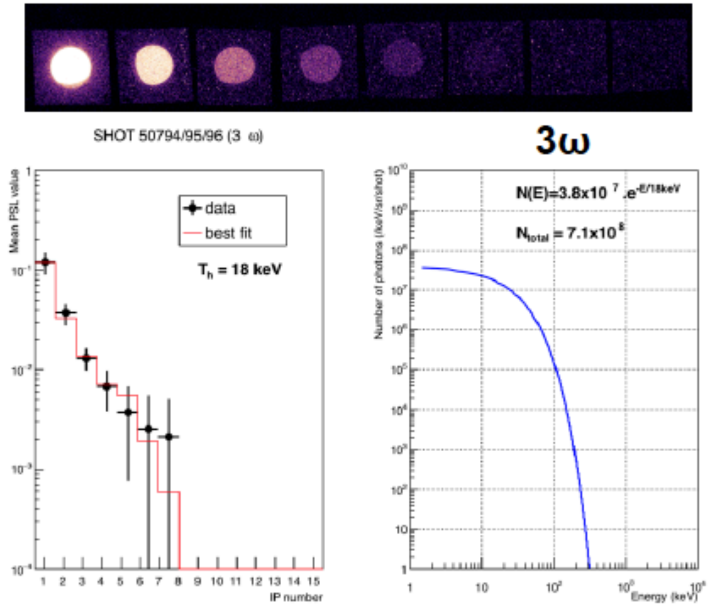
”Coupled hydrodynamic model for laser-plasma interaction and hot electron generation” A. Colaitis, et al. PHYSICAL REVIEW E 92, 041101(R) (2015)

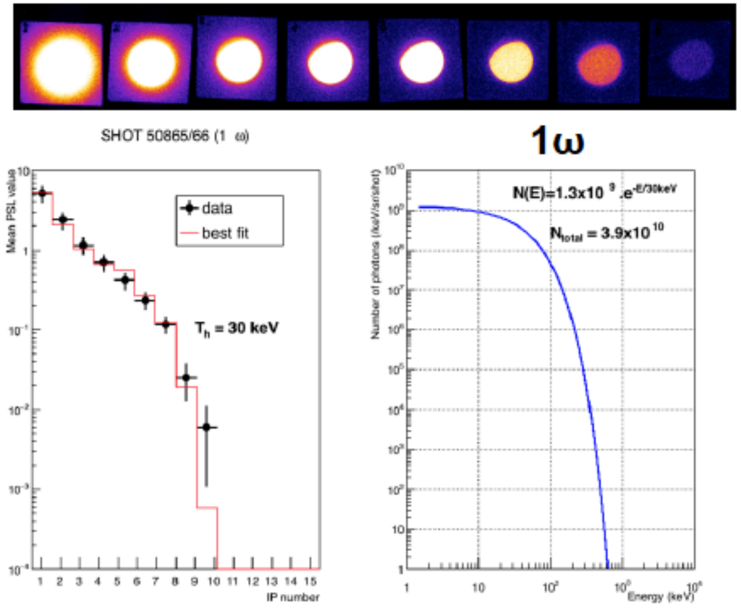
PALS: accurate hot electron characterization

Simultaneous characterisation by: i) X-ray K-α imaging, ii) X-ray spectroscopy, iii) Bremsstrahlung spectroscopy



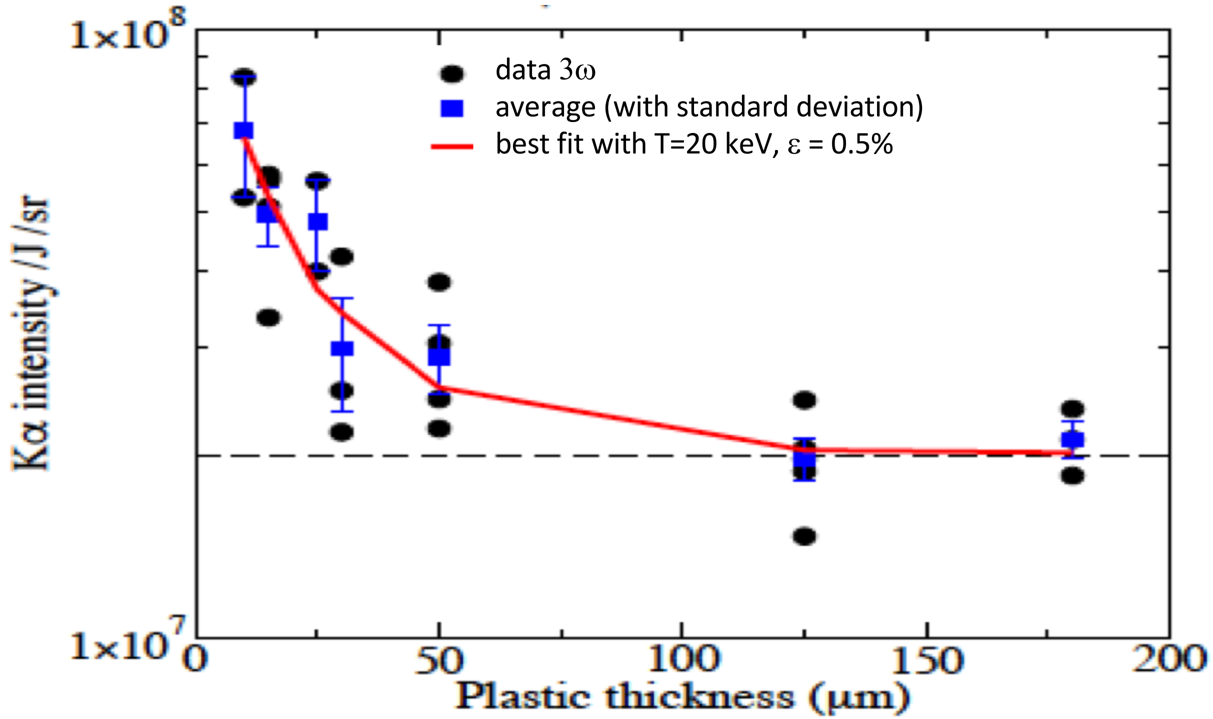






PALS: accurate hot electron characterization

Hot electrons: results



Ti Photon fluxes reconstructed from x-ray spectroscopy for 3ω irradiation

Main source of hot electrons in our conditions is SRS

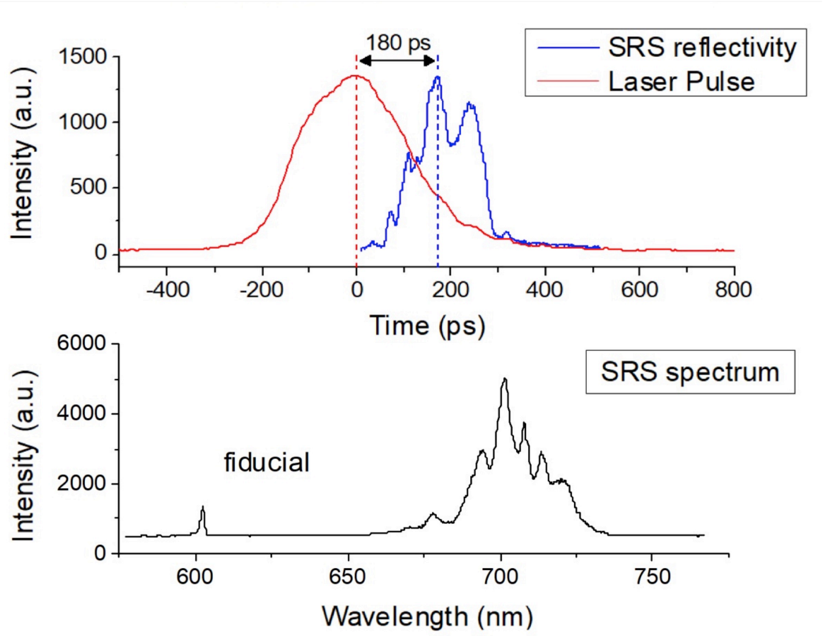
HE characteristics at 3ω and 1ω

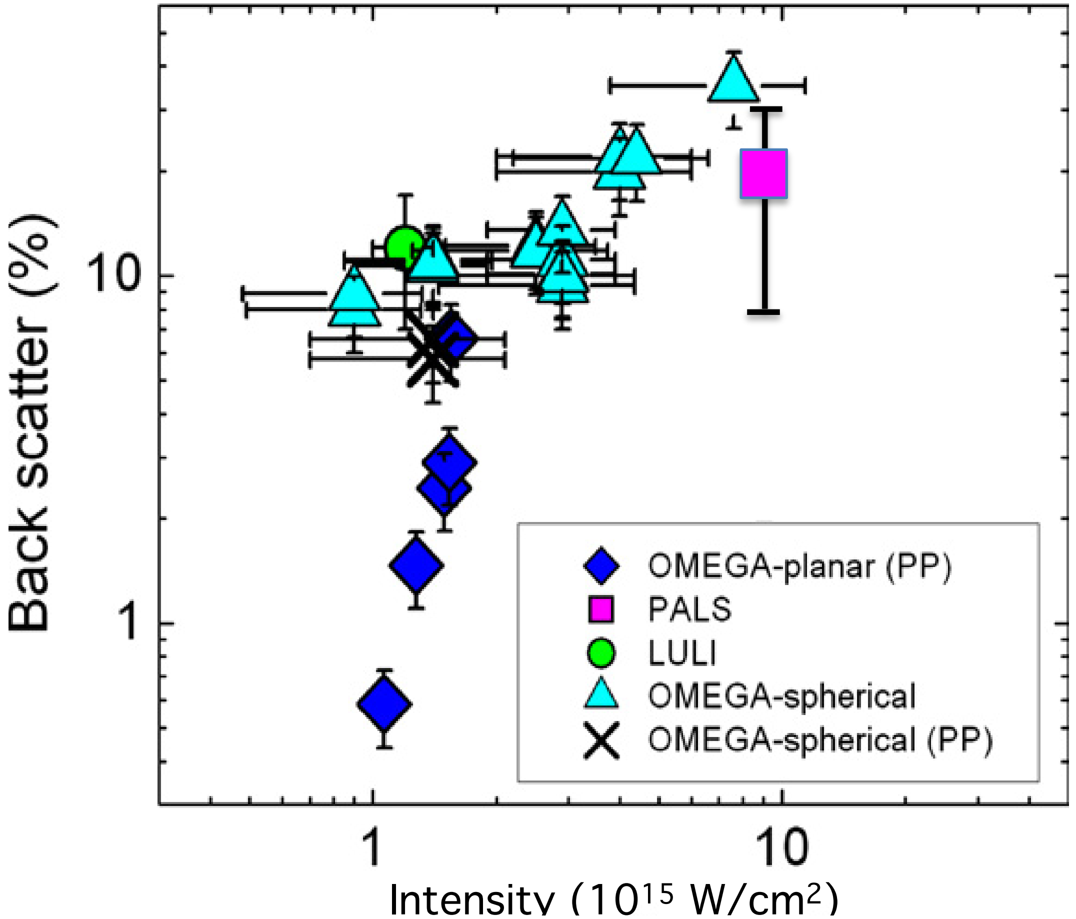
	3ω, $E_{laser} \approx 200J$	1ω, $E_{laser} \approx 650J$
T_{e-} (keV)	20^{+15}_{-8}	38^{+57}_{-12}
$\varepsilon_{laser \rightarrow e-}$ (%)	$0.65^{+1}_{-0.14}$	$2.66^{+3.45}_{-0.13}$

Parametric Instabilities

Reflectivity

- ≤ 10 % inside lens cone
  ≤ 15 % outside
- mainly dominated by SBS





G. Cristoforetti, et al. "Experimental observation of parametric instabilities at laser intensities relevant for Shock Ignition" Europhysics Letters, 117, 35001 (2017)

PALS expt: conclusions

- At 3ω, hot electron temperature of ~ 20 keV and an energy conversion ≤ 1%, have been measured

- Reflectivity ≤ 25 % mainly dominated by SBS

- At 1ω, both hot electron temperature and energy conversion increase (T ~ 40 keV, ε ≤ 3%)

- Main source of hot electrons in our conditions is SRS

- Lateral heat transport in the overdense region is important and reduces the shock pressure

- CHIC simulations reproduced the hot electron characteristics at 3ω and (with some modifications to the scaling laws) at 1ω

- In order to reproduce experimental results it is essential to take the effects of hot electrons into account self-consistently.

Summary

1) What is shock ignition

2) The problem of hot electrons and Experiments at Omega-EP

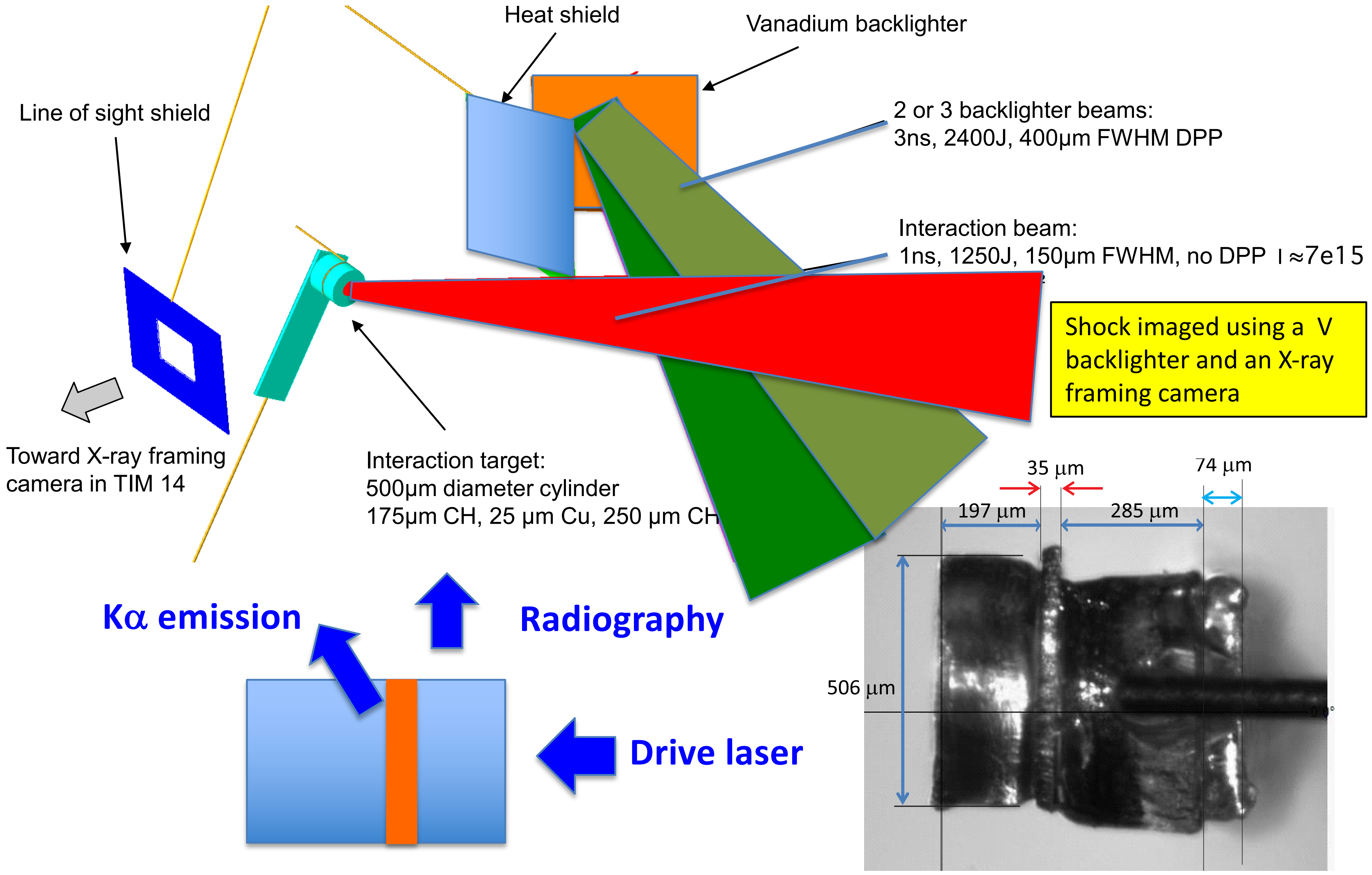
3) Roadmap to shock ignition

- Omega EP

☐ Preliminary results from planar experiments on formation of strong shocks and hot electron effects on shock dynamics

- Experiment supported by EUROFusion …
- Collaboration experiment involving CELIA, JIHT, UPM, INO-CNR, UOY, RAL, LULI URome, UCanaria

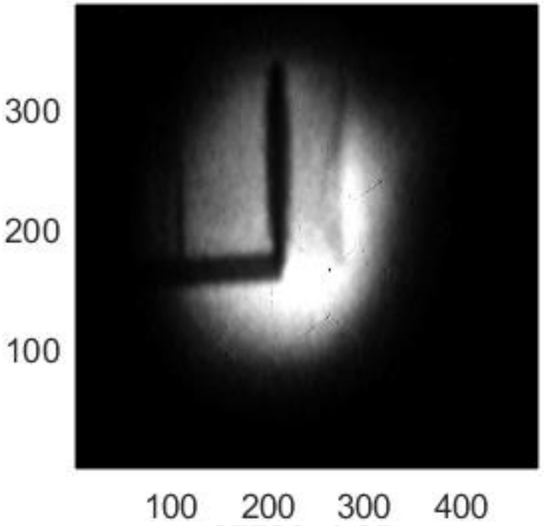
Experiment done on OmegaEP to evaluate effect of hot electrons on shock hydrodynamic (planar geometry)

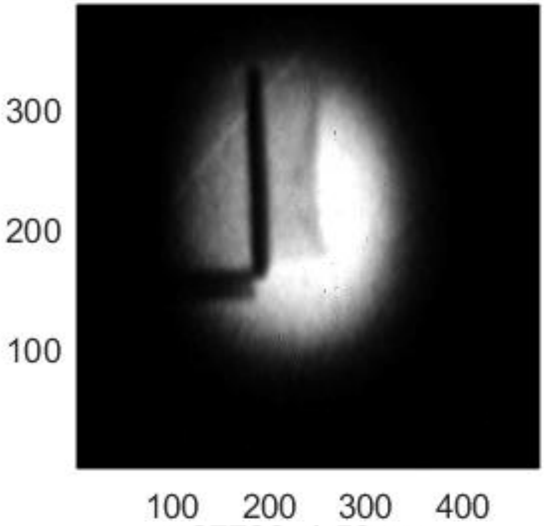


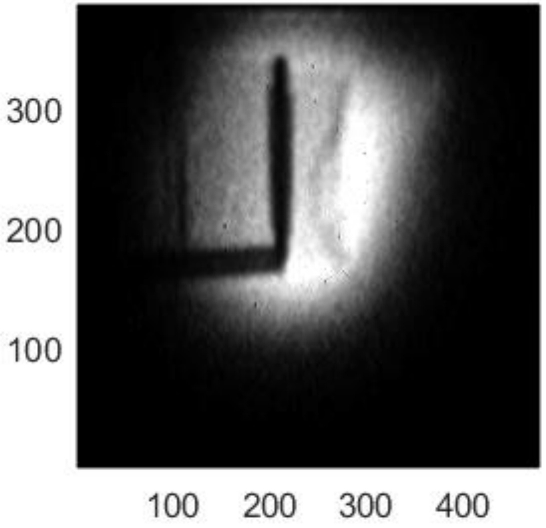
Shock imaged using a V backlighter and an X-ray framing camera

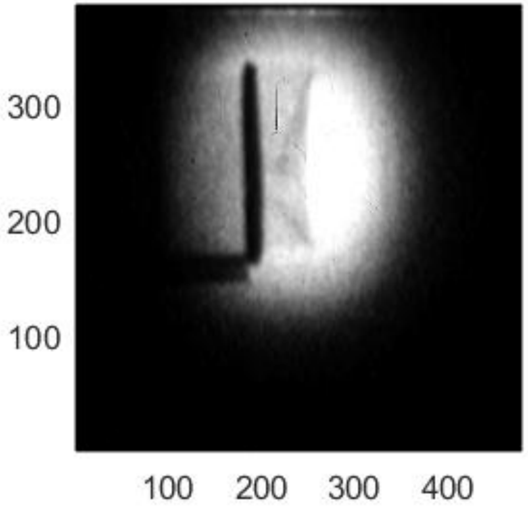
March Shot Day: 2D time-resolved radiographs

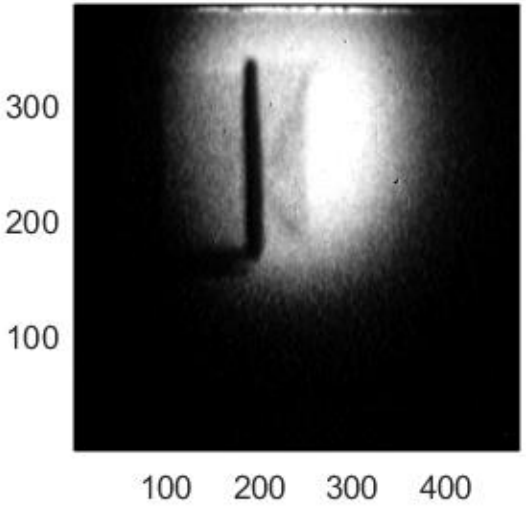
radiography images at several times allows to reconstruct the shock propagation inside the front CH.


s27785, 0.50 ns


s27786, 0.75 ns

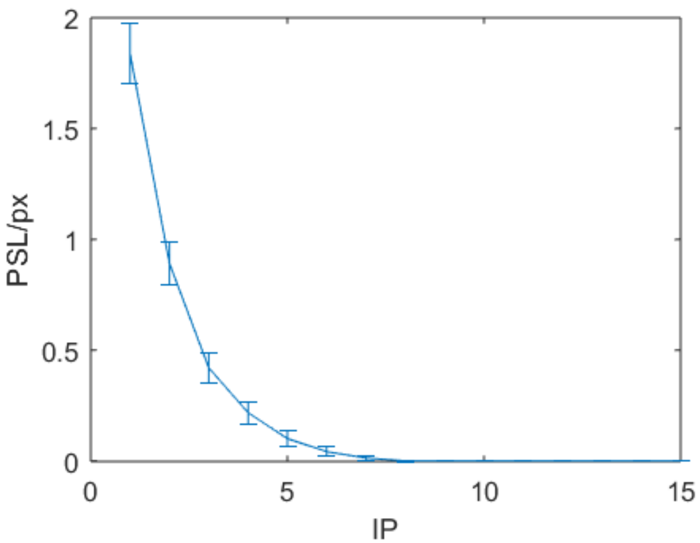

s27785, 1.00 ns


s27786, 1.25 ns


s27786, 1.50 ns

The shock shows an asymmetry due both to the angle of incidence of the laser beam and the effect of hot electrons.

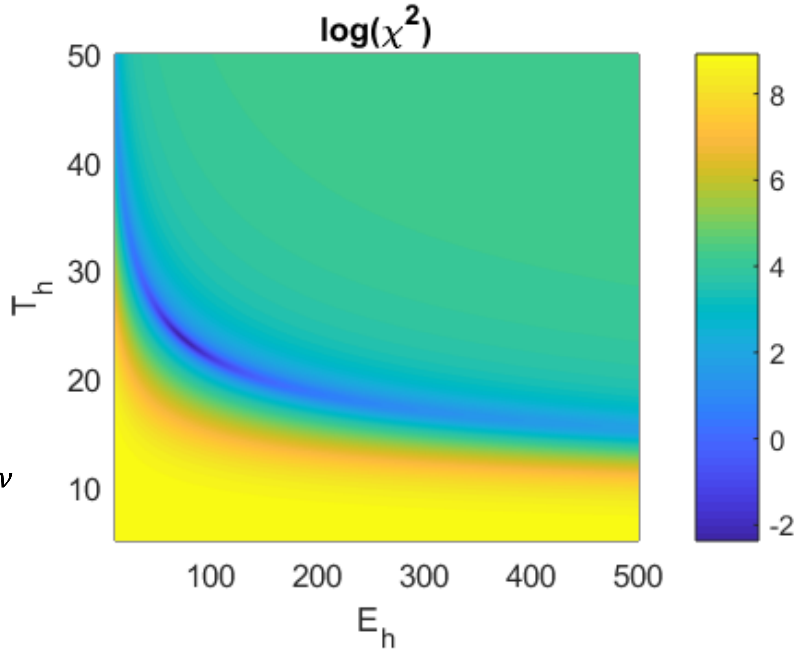
Hot electron temperature and energy are measured using BMXS



Signal on IP of BMXS for shot 27785

- IP 8 to 15: see nothing.
- IP 1 to 4: see two temperature distribution ?
- IP 5 to 7: see hot electrons distribution !

For IP 5 to 7



χ^2 is used to deterime both HE temperature and energy:

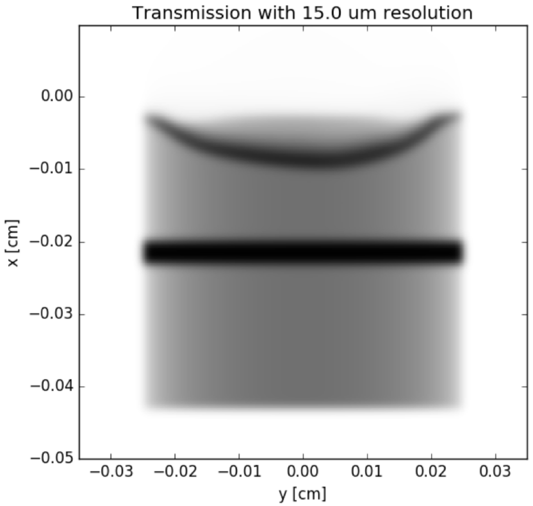
$$S_i(T_h,E_h) = \alpha_i \frac{E_h}{1.5\,T_h}\int F_i(\varepsilon_\nu)\left[\int I_{br}(\varepsilon_h,\varepsilon_\nu)\times f^M(\varepsilon_h,T_h)\mathrm{d}\varepsilon_h\right]\mathrm{d}\varepsilon_\nu$$

$$\tilde{\chi}^2(T_h,E_h) = \frac{1}{n-2}\sum_{i=1}^{n}\frac{[S_i(T_h,E_h)-Q_i]^2}{\delta S_i(T_h,E_h)^2+\delta Q_i^2}$$

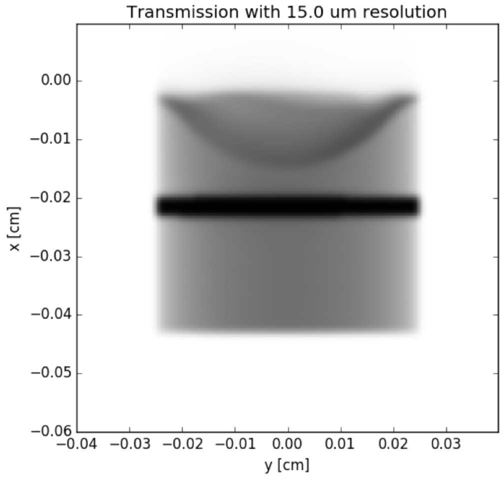
Hot electrons measurement with BMXS show a HE temperature of 25 keV and an energy conversion of 5% ***compatible with CHIC predictions***

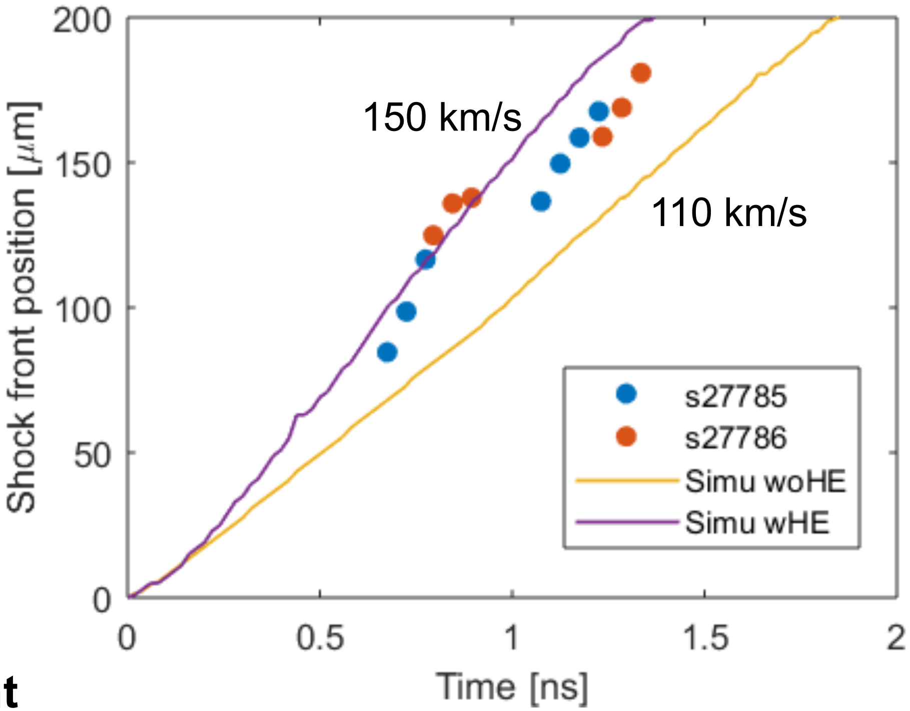
Synthetic radiographies with hot electrons show better agreement with experiment

Simulation woHE

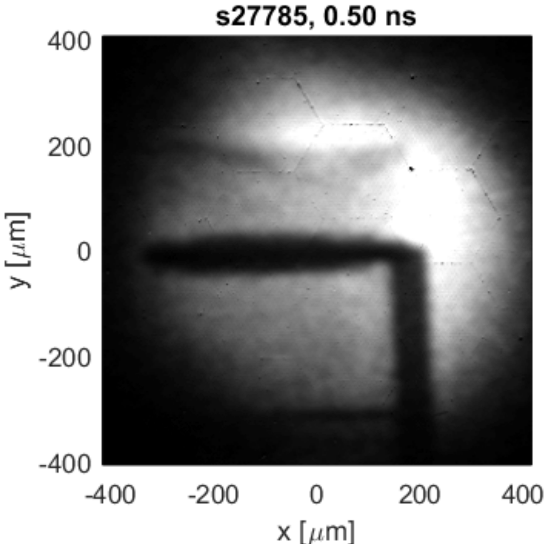


Simulation wHE



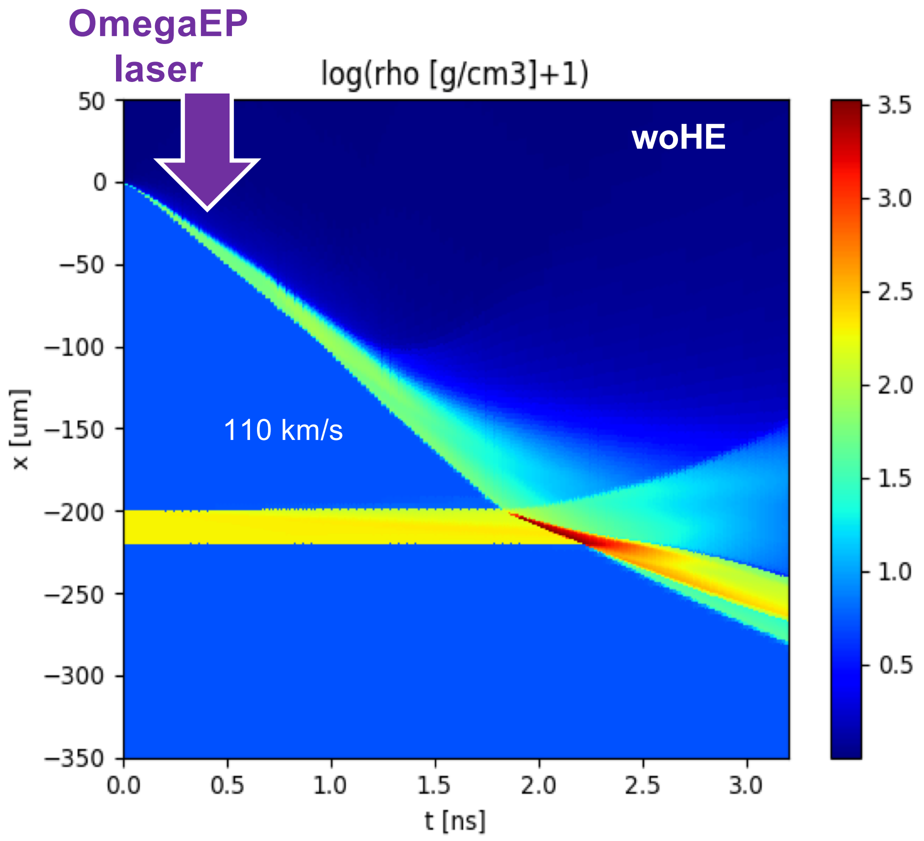


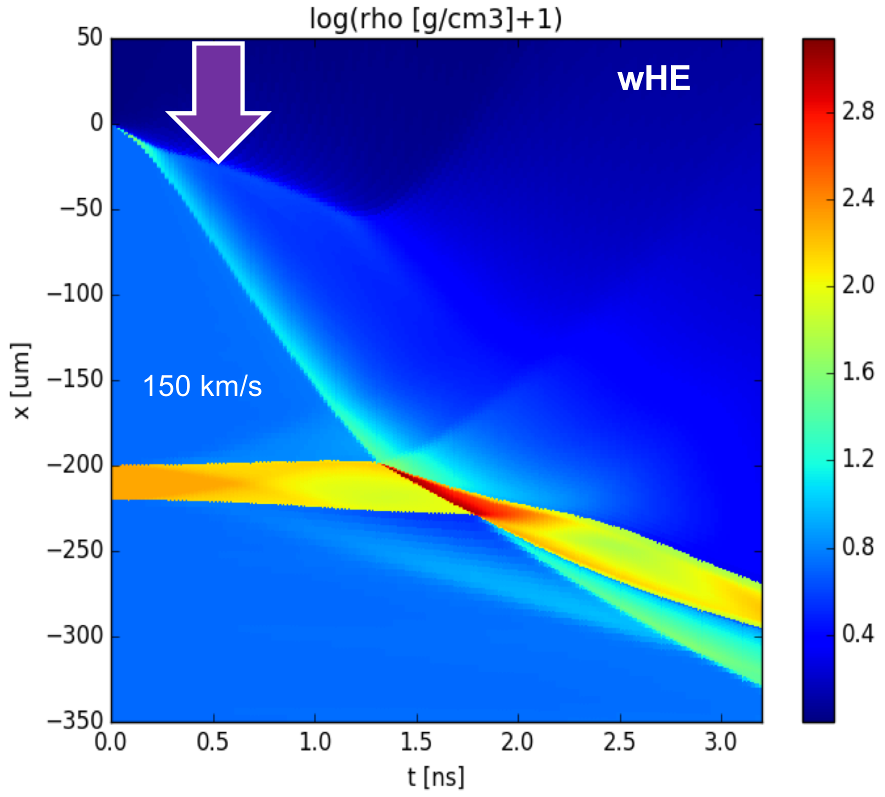
0.5 ns



Experiment

Displaying the density in the (x,t) plan shows the effect of hot electron heating on shock dynamics



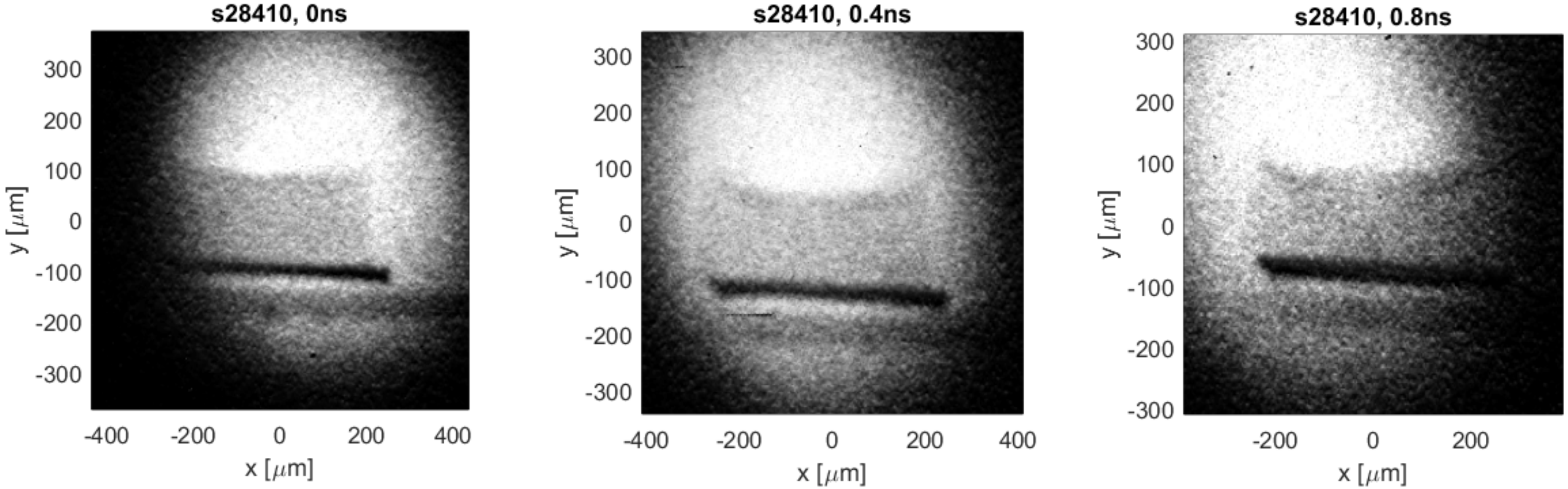


	woHE	**wHE**
Shock pressure in front CH	~100 Mbar	~150 Mbar
Shock breakout CH to Cu	1.82 ns	1.32 ns
Shock breakout rear of Cu	2.25 ns	1.82 ns

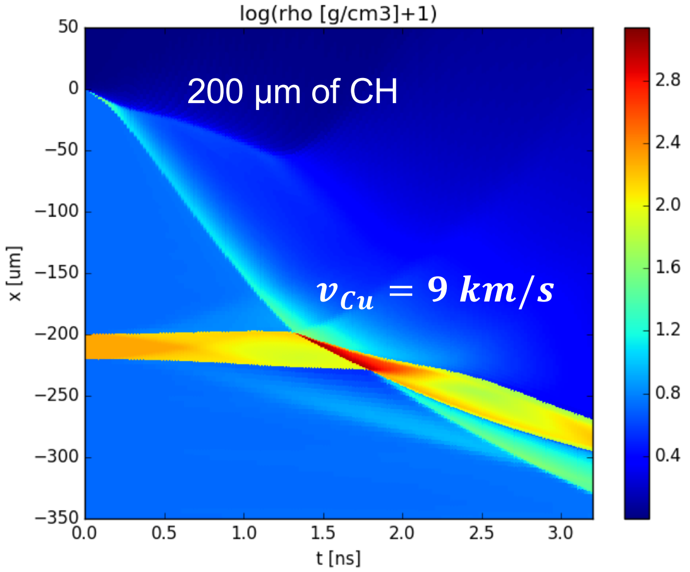
Effect of the HE on the hydrodynamic:

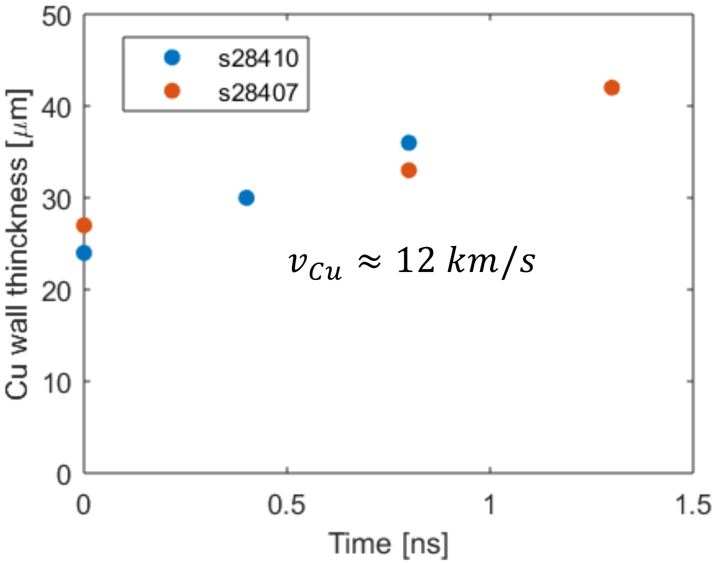
- **Faster main shock**
- **Expansion of shocked CH**
- **Expansion of the Cu layer**

The expansion of copper layer due to hot electron heating has been clearly observed.



175 µm CH facing laser



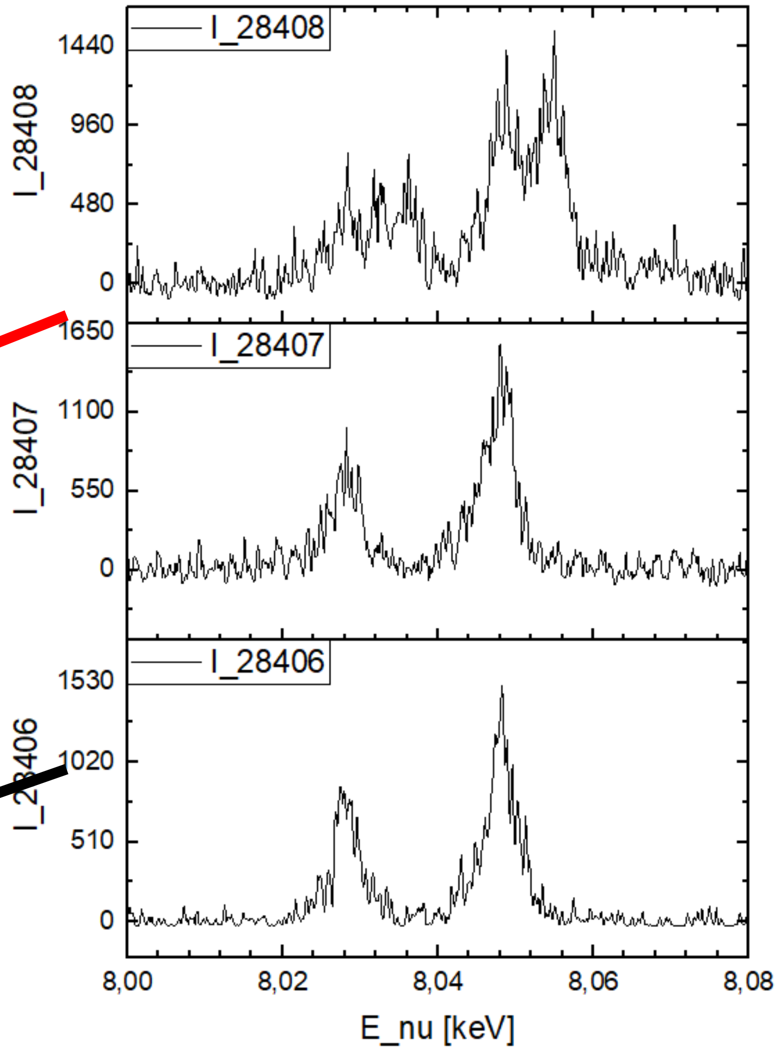


The measured expansion velocity of the copper layer is coherent with simulation

K_α spectrometry

- Two diagnostics measure the K_α emission from copper:
  - ZNVH: Zinc Von Hamos, crystal reflection recorded on IP.
  - HRS: High Resolution Spectrometer, recorder on CCD.

HRS raw spectra near Cu Kα line

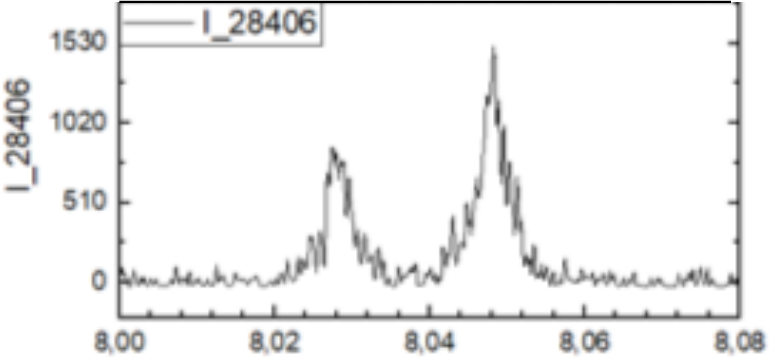


Broadened/split lines = WDM

Changing beam energy and plastic overlayer thickness

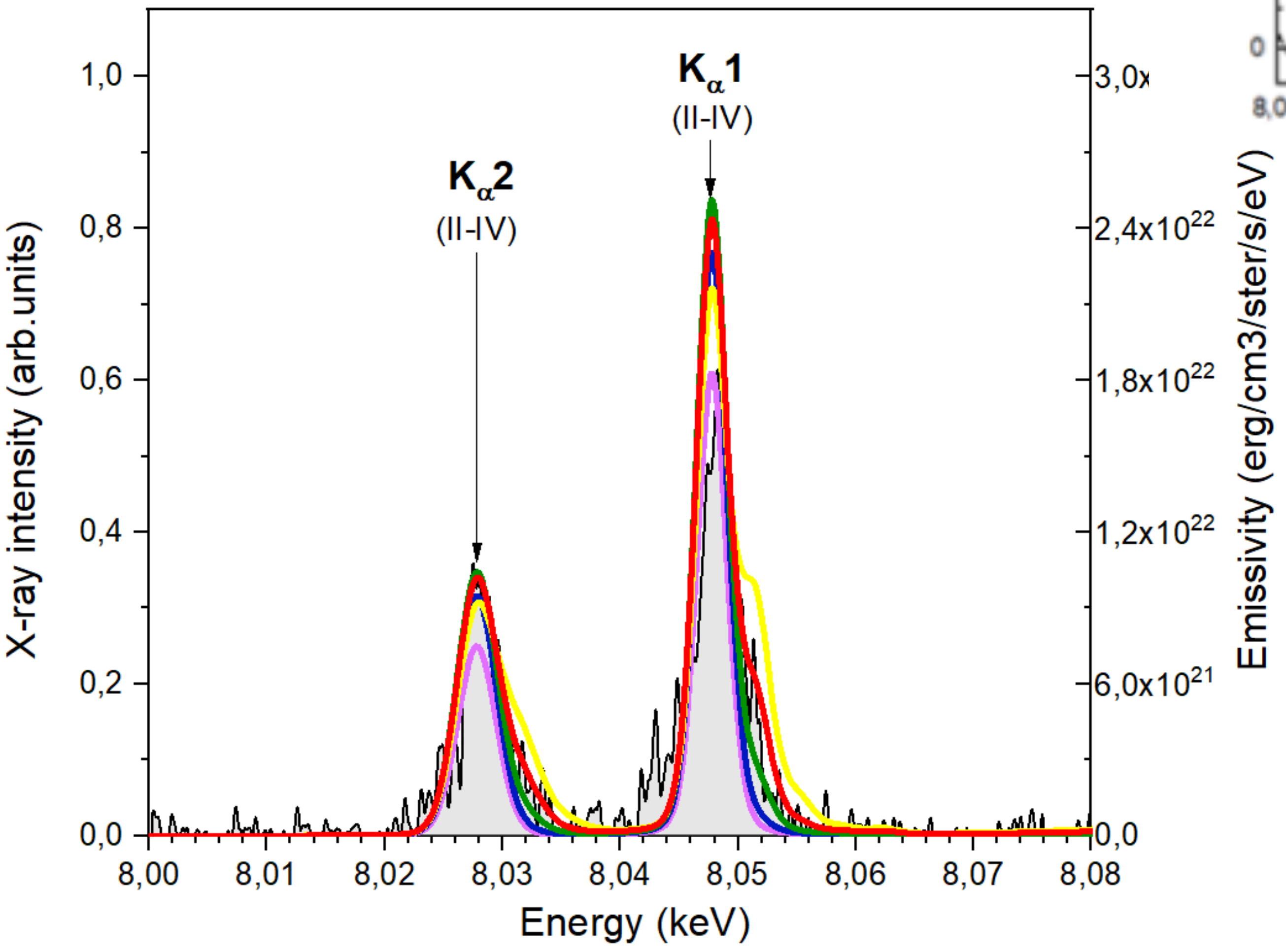
Simple / narrow line case

Modeling by PrismSpect



Narrow line case

N_i=8e22=N_{solid}, N_e~ 3e23 cm-3, T_{hot}=10 keV (1

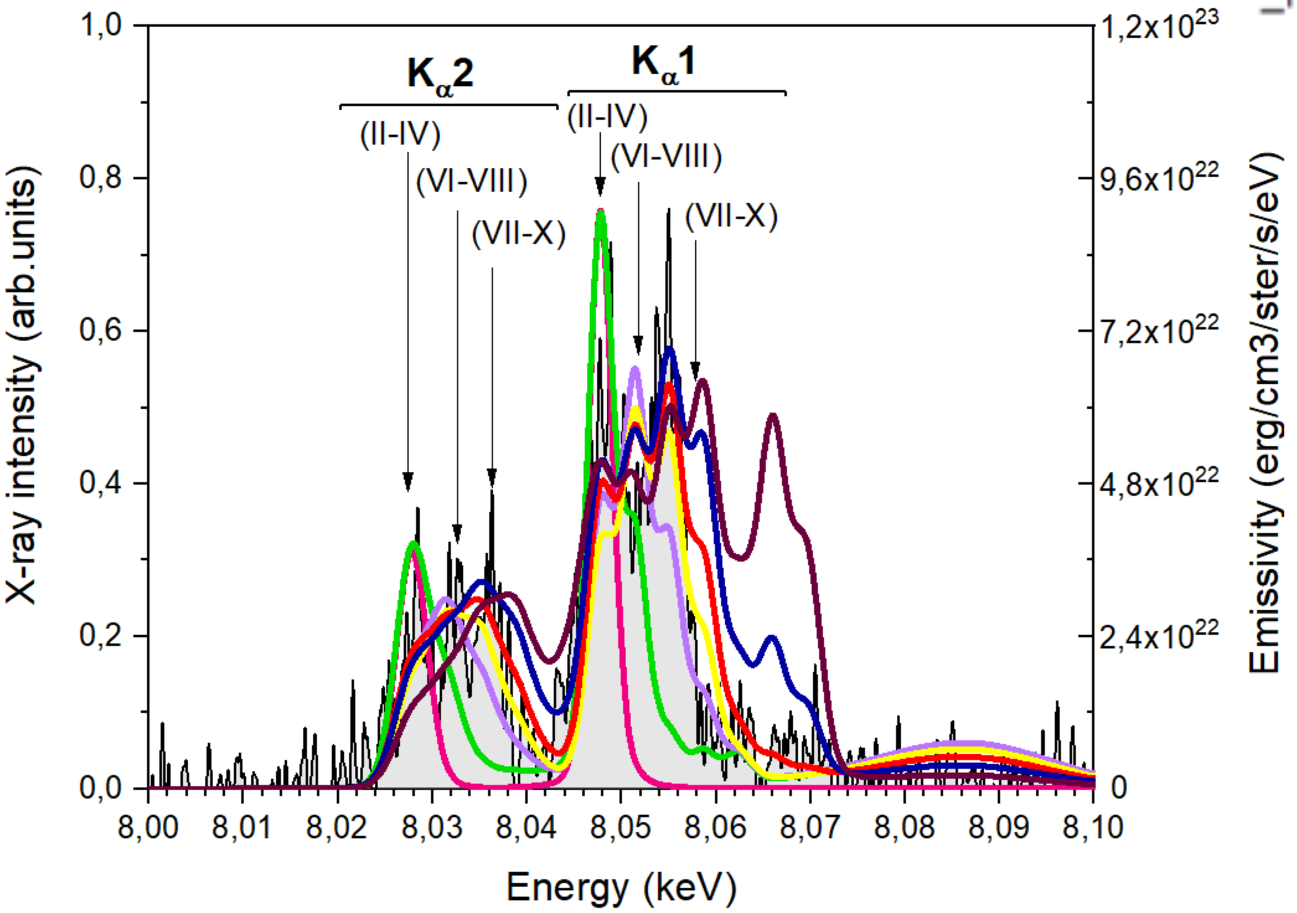


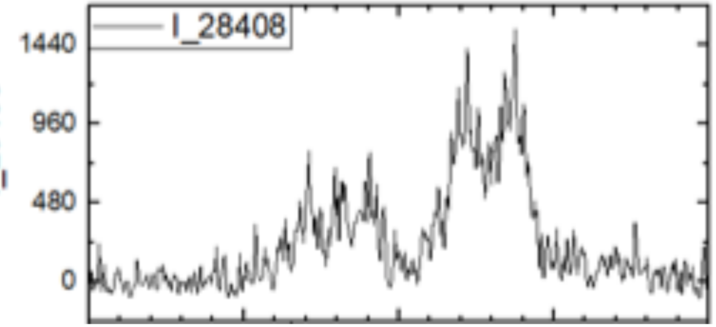
Shot #28406:
T_e = 22(±5) eV

Modeling by PrismSpect

Broad lines case

T$_{hot}$=10 keV (5%), N$_i$ = 8e22 = N$_{solid}$, N$_{e}$~ 6e23 cm-3





Shot #28408

T$_e$ ~70(±10) eV

with definite contribution from colder "surrounding" target area (Te < 20 eV)

Omega EP expt: conclusions

- **Hot electron temperature of ~ 25 keV and an energy conversion of 5%, i.e. a total energy of ~60 J have been simultaneously measured, in agreement with predictions from CHIC simulations.**

- **CHIC simulations reproduced the shock velocity when the effects of hot electrons are taken into account. They predict an increase of 50% in shock pressure with hot electrons**

- **Synthetic radiographies roughly reproduce the shape of the shock front when hot electrons are taken into account**

- **The copper layer expands sur to preheating induced by hot electrons and a WDM state is produced which is in agreement with results from Kα spectroscopy**

Perspectives

Both PALS and Omega EP experiments show that:

- We need to develop and optimize diagnostics dedicated to study the dynamics of very strong shocks in materials preheated by hot electrons and for the characterization of hot electrons
- Modellisation of laser-plasma interaction and shock dynamics must self-consistently take into account the effects of parametric instabilities, the generation of hot electrons and the effect they have on target (increase in pressure but also preheating-induced expansion). Such modelisation requires developing and “tuning” advanced hydrodynamics codes

Summary

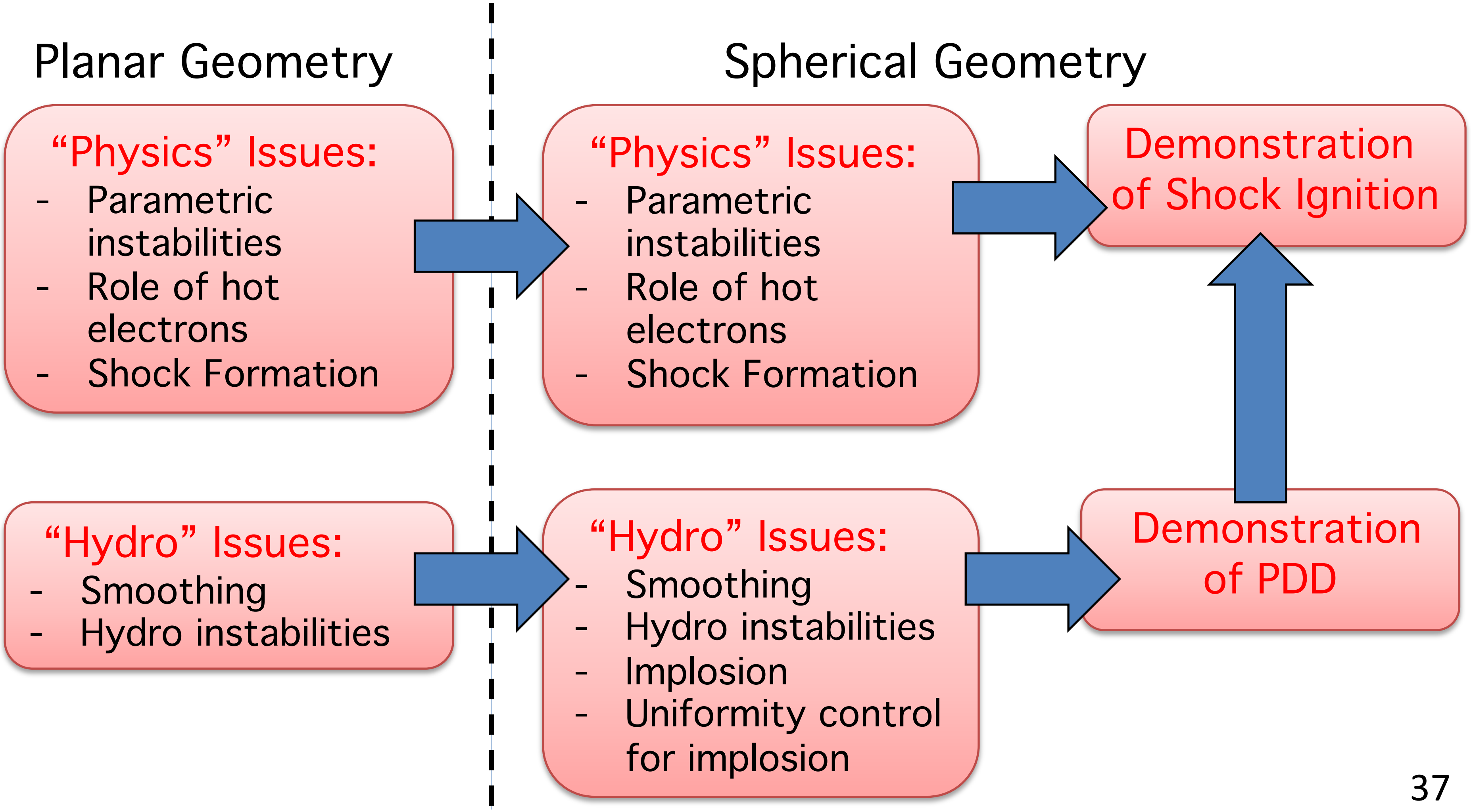
1) What is shock ignition

2) The problem of hot electrons and Experiments at PALS and Omega-EP

3) Roadmap to shock ignition

Road map to shock ignition

How to approach the final goal of "Performing shock ignition demonstration experiments " ?



Planar Geometry

"Physics" Issues:
- Parametric instabilities
- Role of hot electrons
- Shock Formation

"Hydro" Issues:
- Smoothing
- Hydro instabilities

Spherical Geometry

"Physics" Issues:
- Parametric instabilities
- Role of hot electrons
- Shock Formation

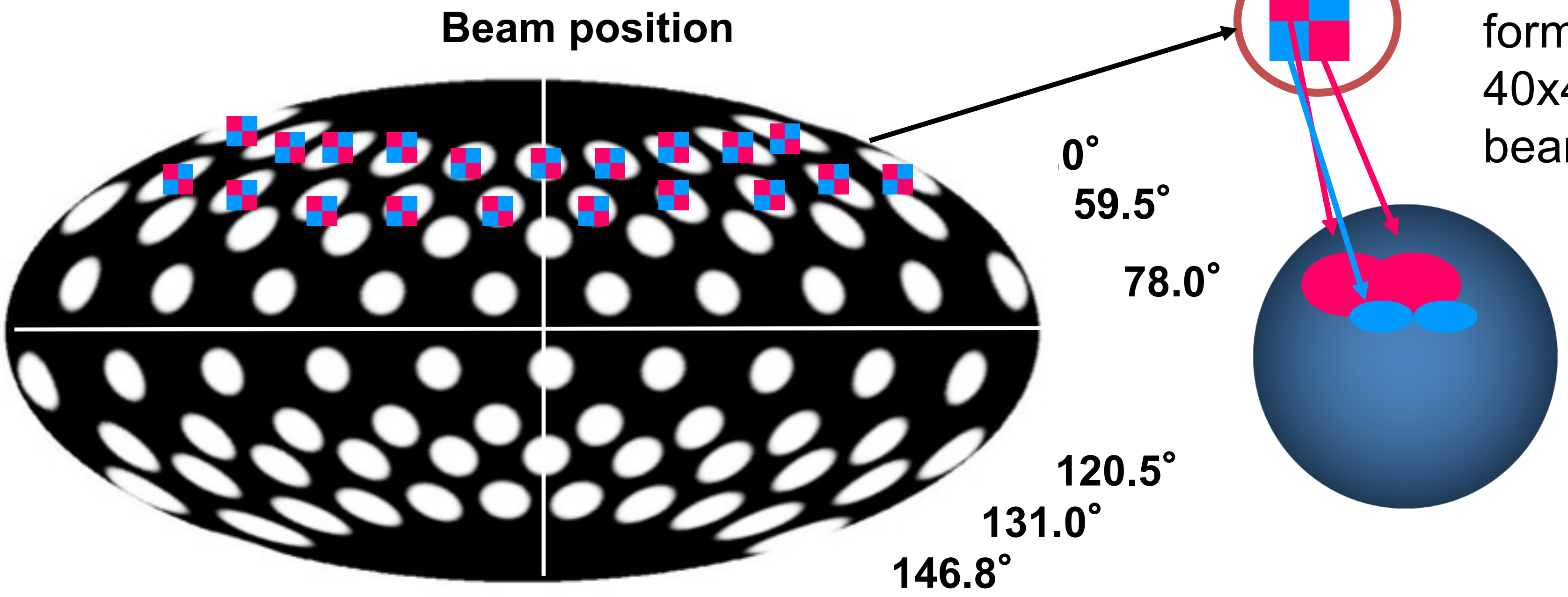
"Hydro" Issues:
- Smoothing
- Hydro instabilities
- Implosion
- Uniformity control for implosion

Demonstration of Shock Ignition

Demonstration of PDD

Polar Direct Drive (PDD)

An example of how it could be done…

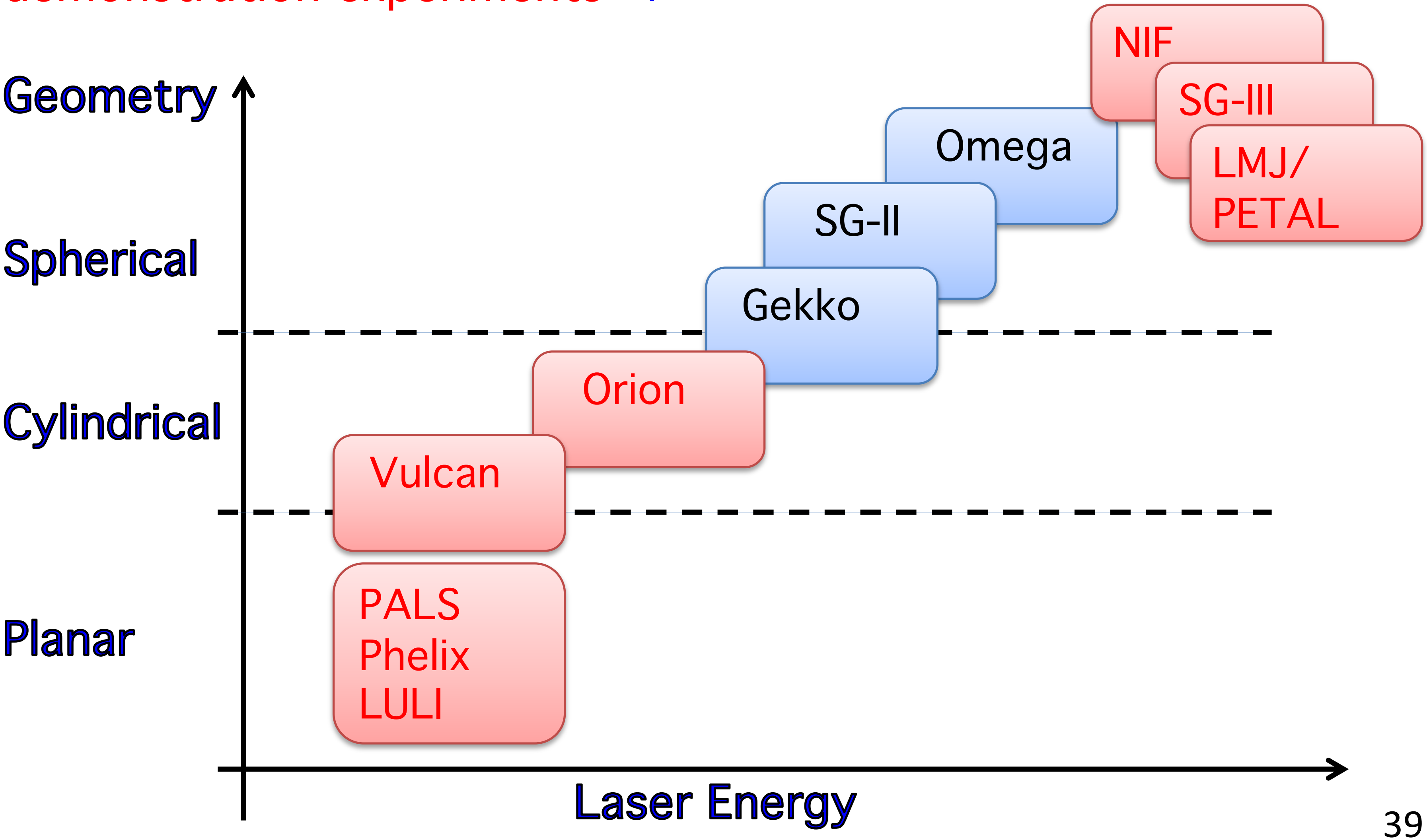


1 LMJ Quad
formed from 4
40x40 (cm)
beams

Split
and repointed
on a sphere
For optimal
illumination

Road map to shock ignition

How to approach the final goal of "Performing shock ignition demonstration experiments" ?



Summary / Conclusions

- Interesting physics which needs to be understood and mastered

- SI can be demonstrated at NIF, LMJ or or the Shenguang-III laser facility in China in the next decade

- BUT development of a full programme relies on:

  Scientific credibility: physics issues addressed using:

  - “Smaller” facilities: PALS, ORION, Vulcan, LULI, Phelix, Gekko, Shenguang-II
  - intermediate-scale facilities: OMEGA, Shenguang-III P

- Support of EUROFusion has been, and is, important

Thank you for your attention !