The Creation of Large-Volume, Gradient-Free Warm Dense Matter with an X-Ray Free-Electron Laser

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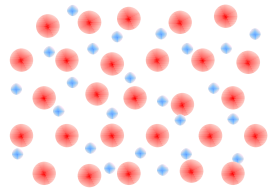


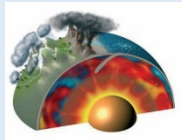
Heated solid
« Warm dense matter »

$\rho \geq \rho_{solid}$
$0.1\ eV < T < 100\ eV$

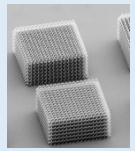
Strongly correlated and partially degenerated

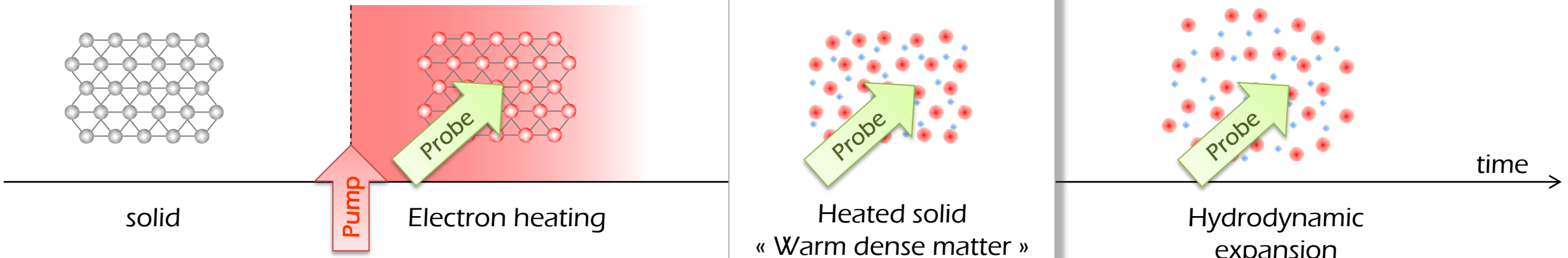
- Inertial fusion confinement

- Planetary interiors



- Laser ablation



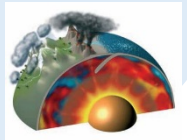


Proton beam		
10-20 eV	solid	ps
Nanosecond laser		
10-20 eV	compressed solid	ps
Femtosecond laser		
1-2 eV	solid	fs
XFEL		
10-20 eV	solid	fs

Strongly correlated and partially degenerated

- Inertial fusion confinement

- Planetary interiors



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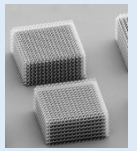
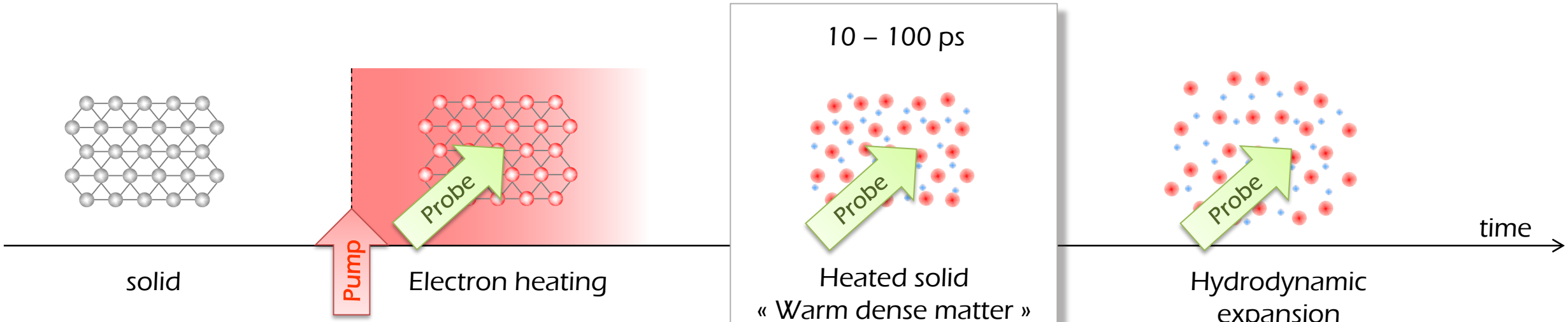




ULTRAFAST HEATING

Out-of-equilibrium

Proton beam
10-20 eV solid ps

Nanosecond laser
10-20 eV compressed solid ps

Femtosecond laser
1-2 eV solid fs

XFEL
10-20 eV solid fs

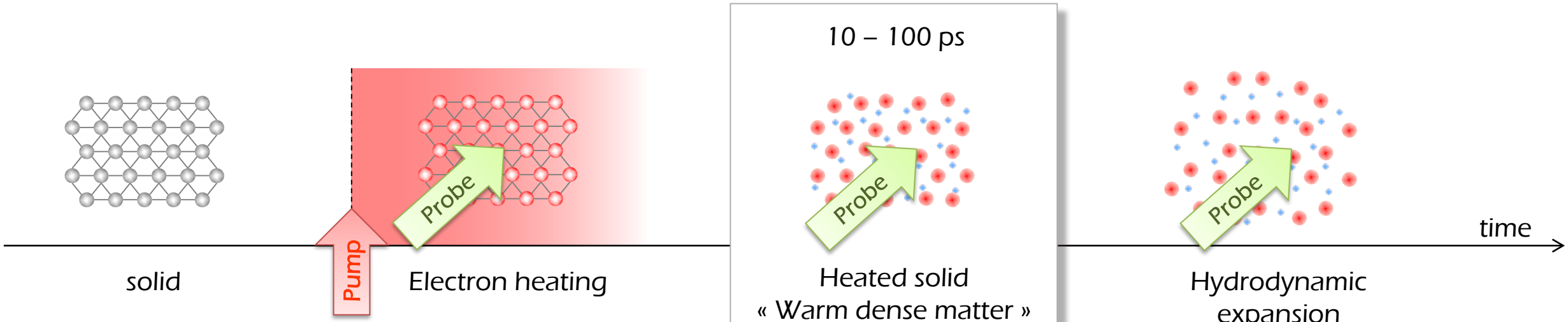
Sample temperature ?

Heating uniformity ?

Electron-ion energy transfer duration ?

Sample relaxation ?

Modification of the electronic structure ?



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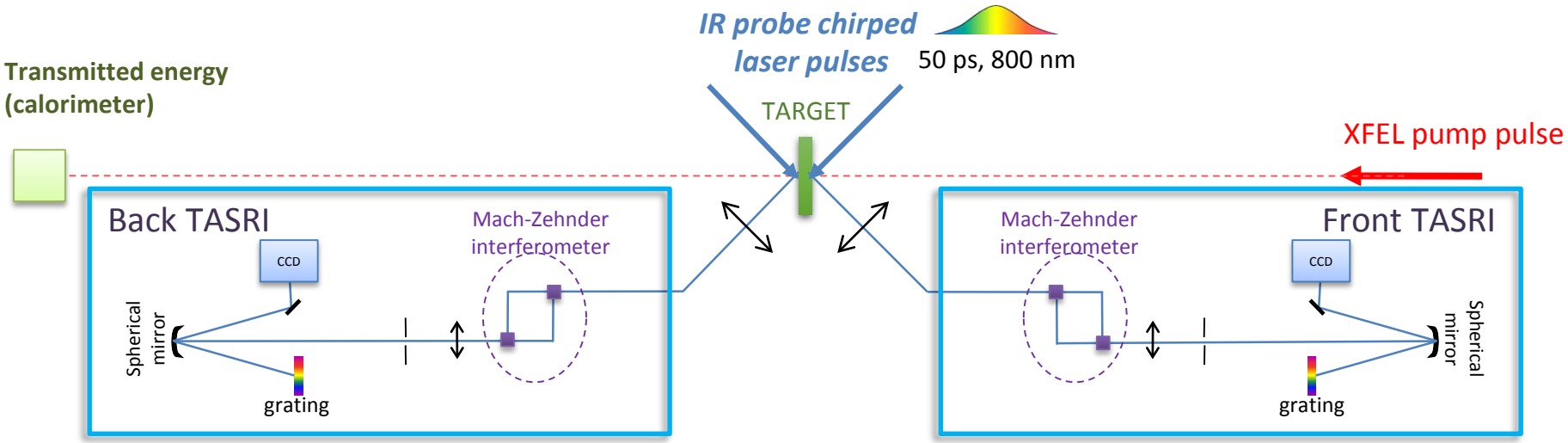


X-ray Pump Probe (XPP) Instrument – SLAC/LCLS

$h\nu \sim 9$ keV

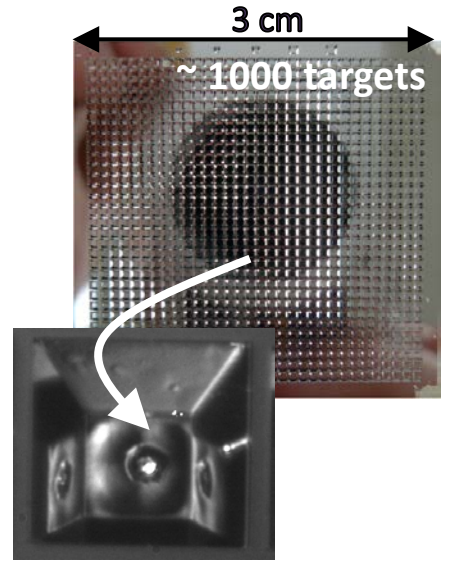
$\tau = 63$ fs – 115 fs

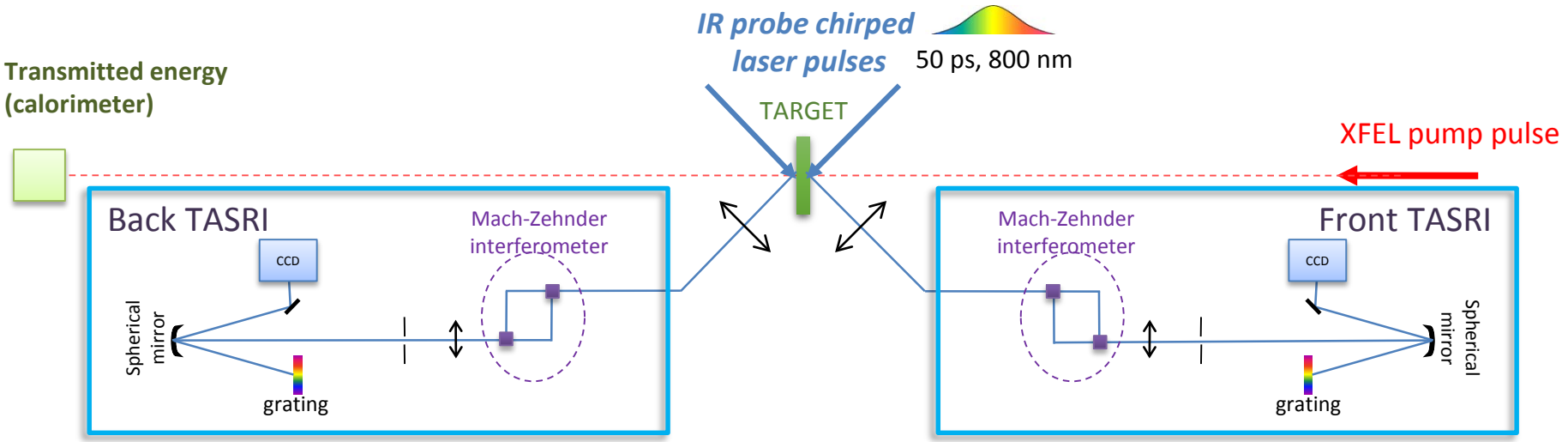
E : 2.2 – 3.7 mJ

σ = 6 x 6 and 15 x 17 µm²

$I = 2 - 5 - 10 \cdot 10^{15}$ W/cm²

Target : Ag foils





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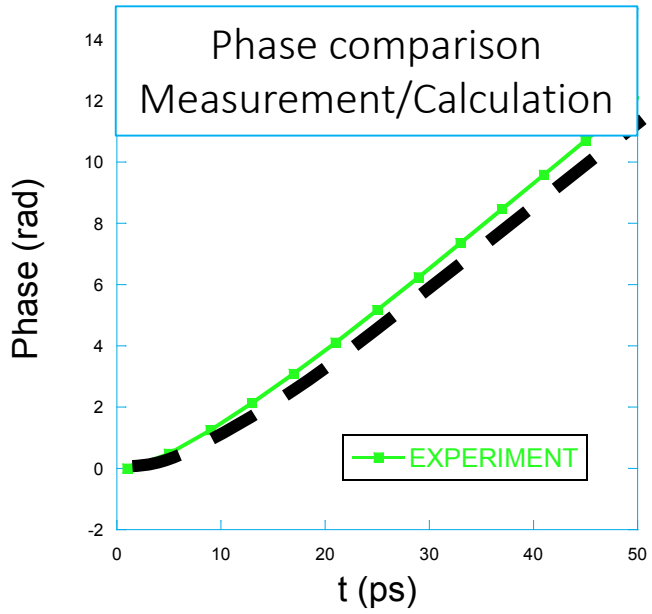
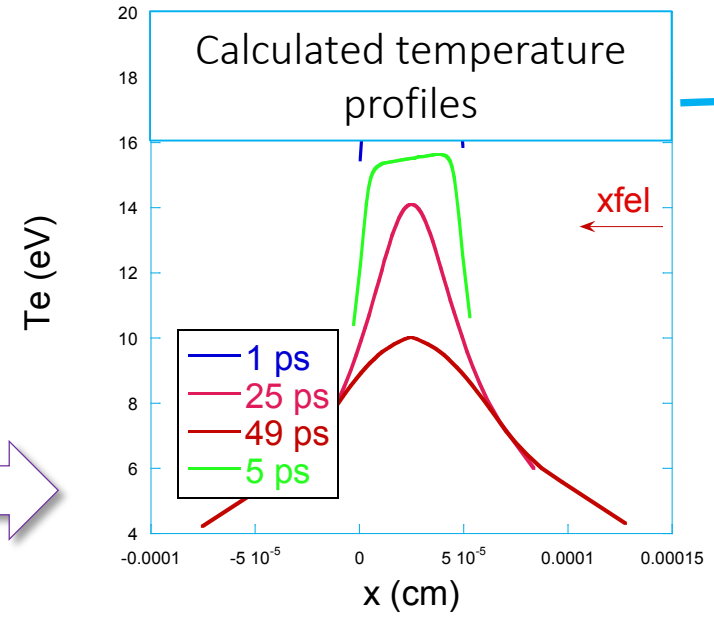
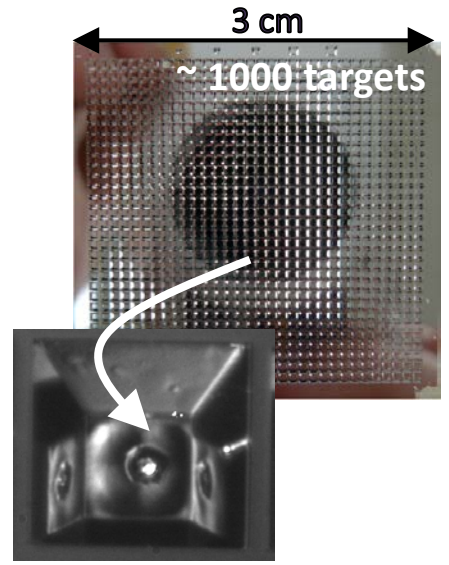


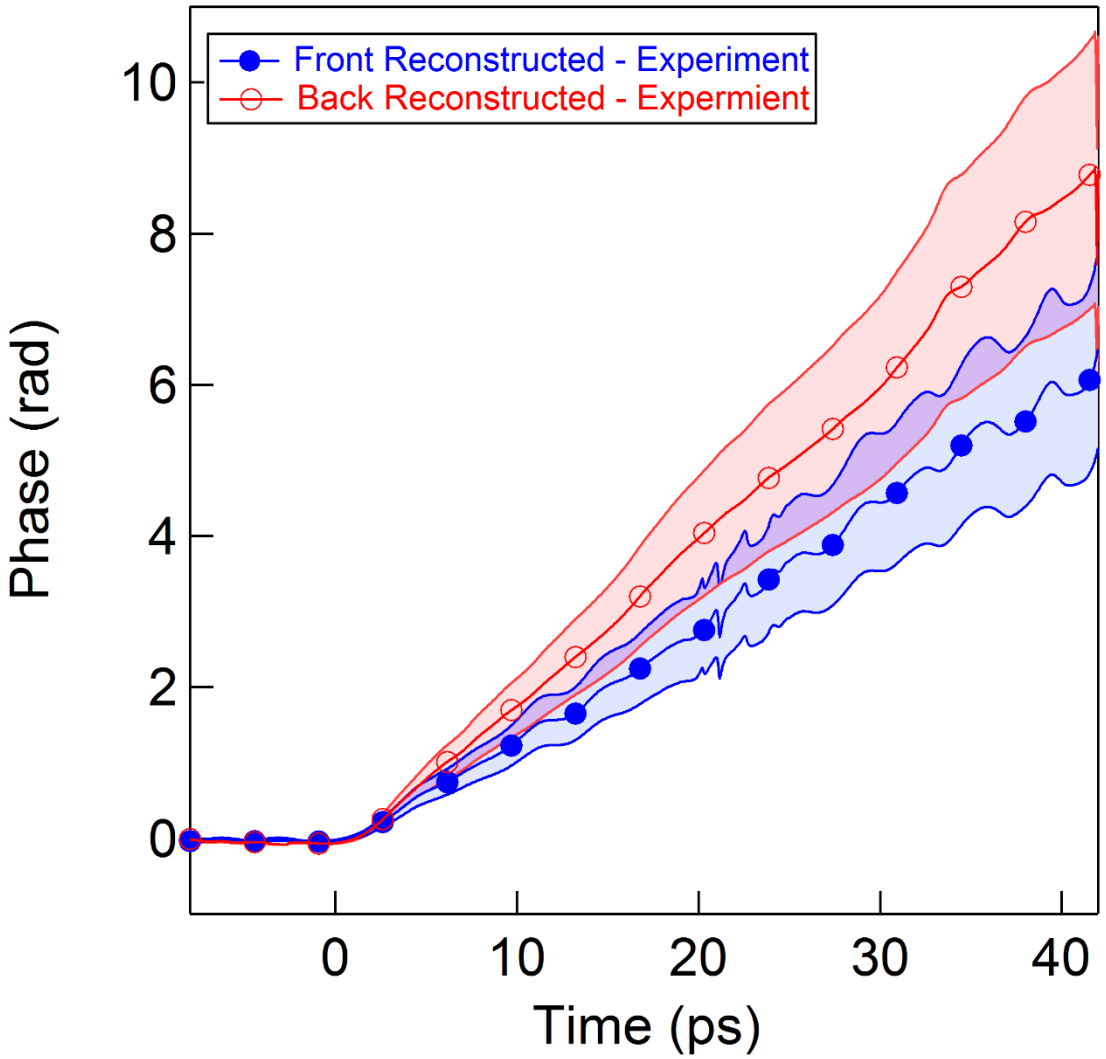


Procedure

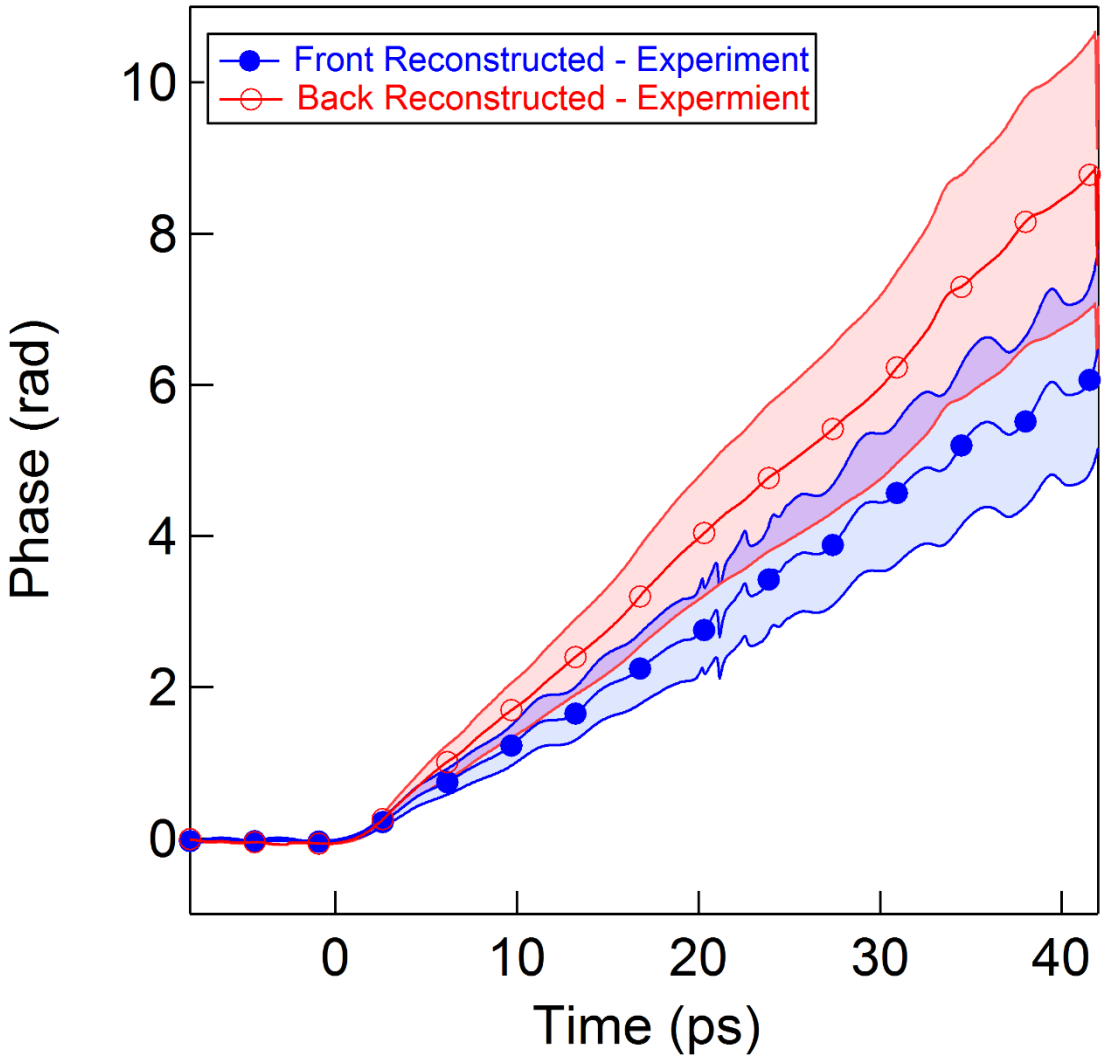
Sample temperature evaluation

Target : Ag foils





Target	X-ray focal spot	X-ray duration	X-ray attenuation
2 µm	15x17 µm²	63 fs / 115 fs	100 % / 50 % / 25 %
2 µm	5x9 µm²	63 fs / 115 fs	100 % / 50 % / 25 %
0.5 µm	**15x17 µm²**	**63 fs** / 115 fs	**100 %** / 50 % / 25 %
0.5 µm	5x9 µm²	63 fs / 115 fs	100 % / 50 % / 25 %



❑ 1D Hydrodynamic code **ESTHER**

P. Combis – CEA-DAM

X-ray energy deposition : Cold opacities tables

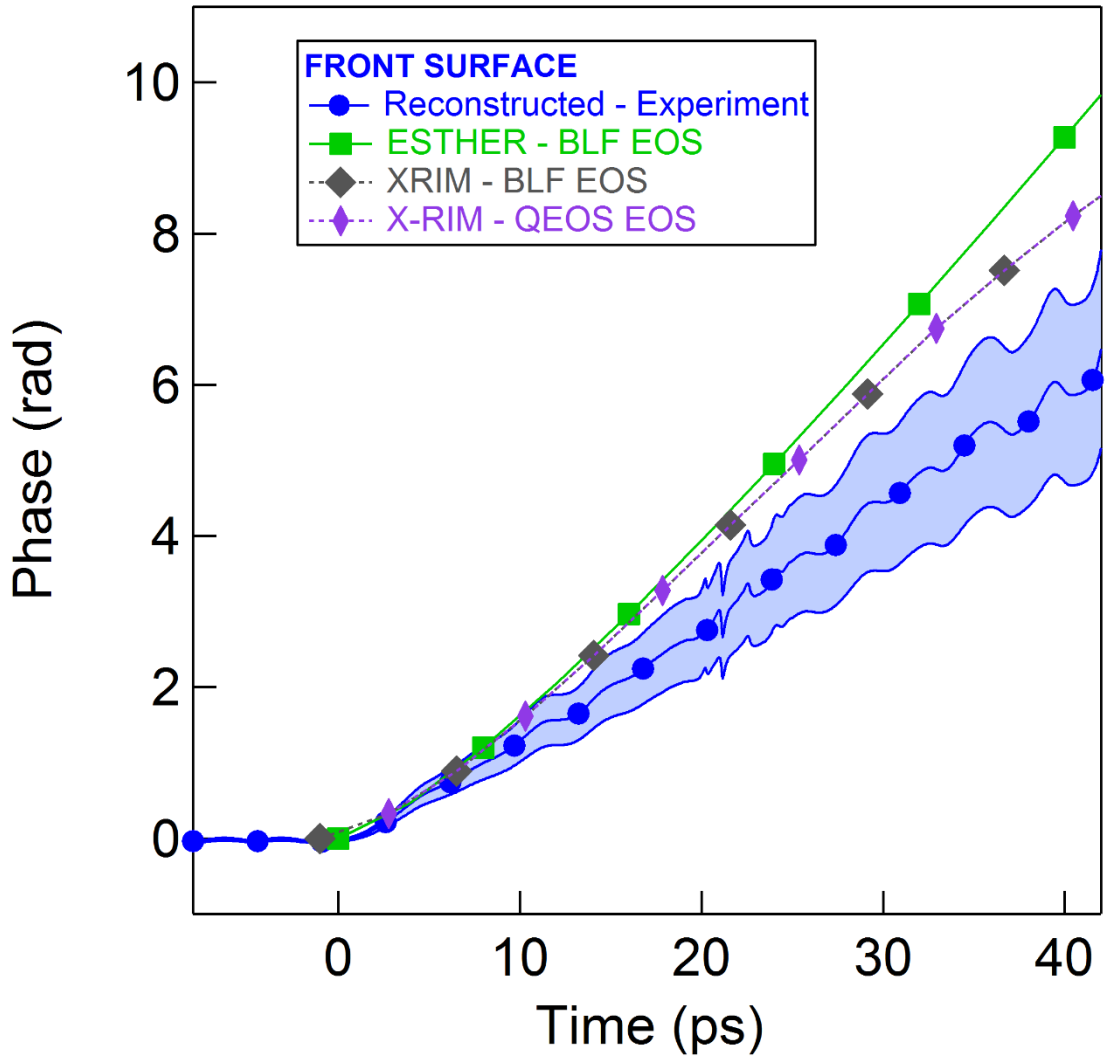
Equation of states : BLF

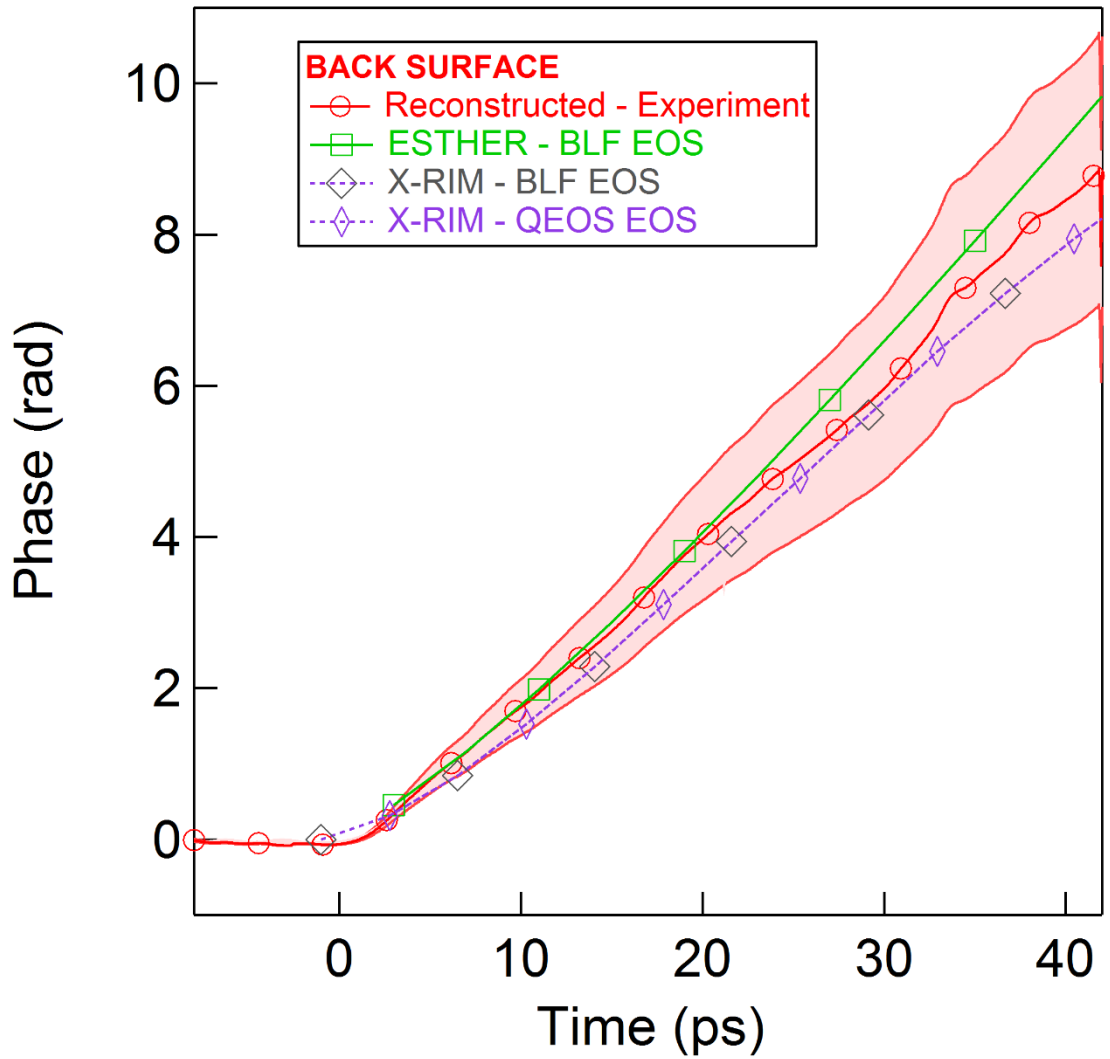
❑ 1D Hydrodynamic /Atomic code **XRIM**

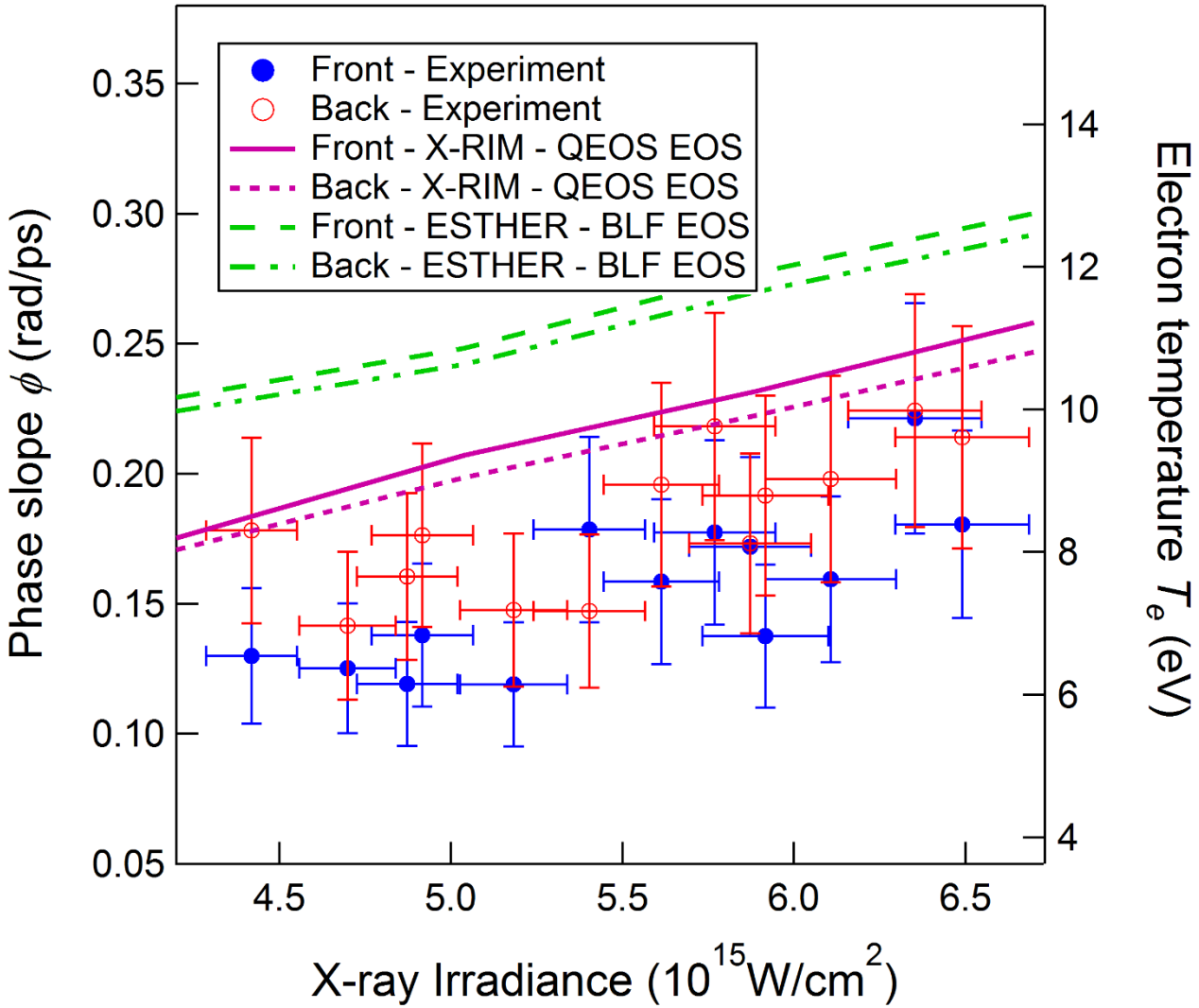
O. Peyrusse – CELIA

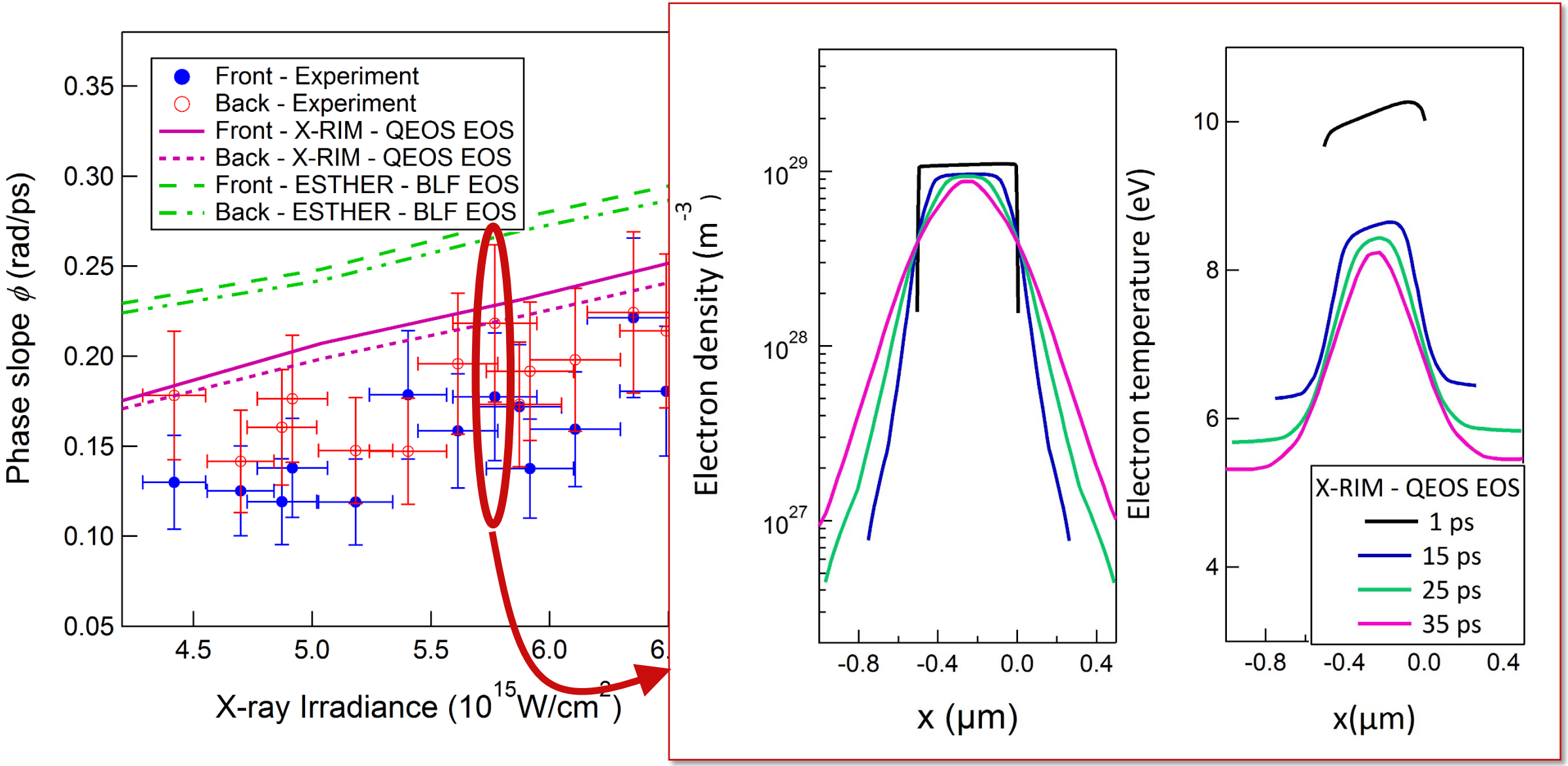
X-ray energy deposition : Photo-absorption – Auger decay

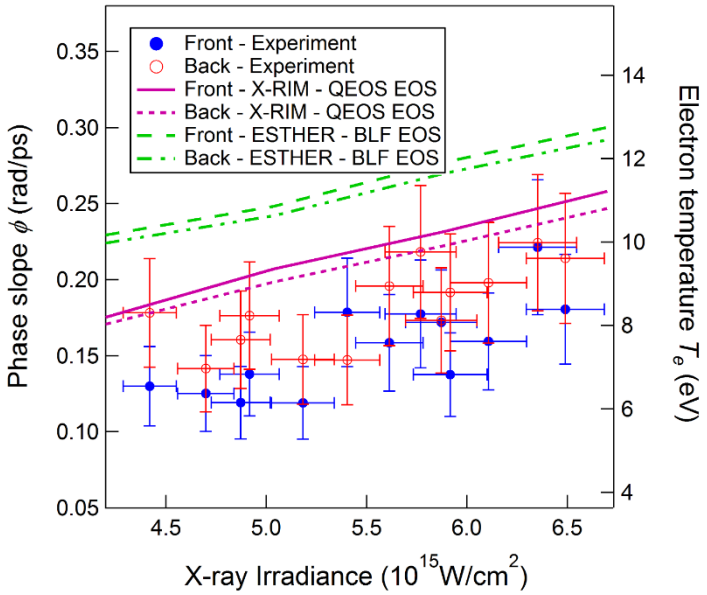
Equation of states : QEOS or BLF

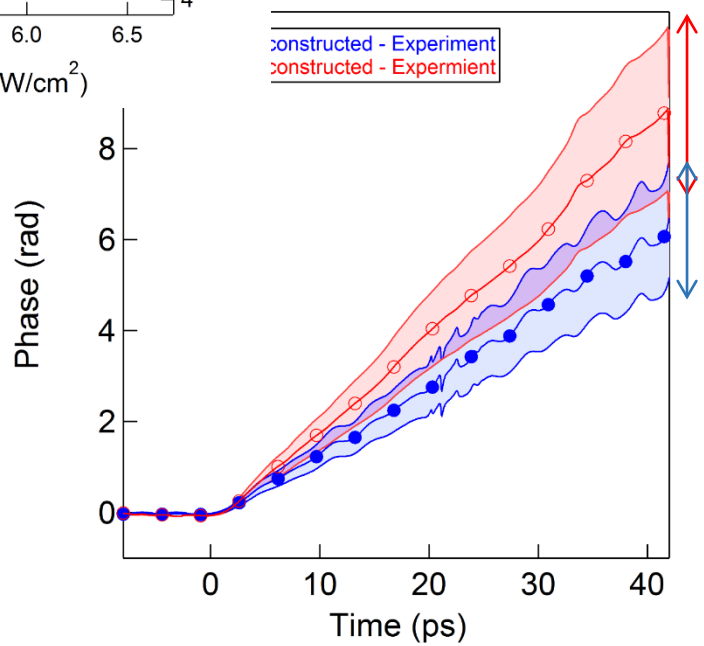

FRONT SURFACE
Reconstructed - Experiment
ESTHER - BLF EOS
XRIM - BLF EOS
X-RIM - QEOS EOS
Phase (rad)
Time (ps)
0
2
4
6
8
10
0
10
20
30
40


BACK SURFACE
Reconstructed - Experiment
ESTHER - BLF EOS
X-RIM - BLF EOS
X-RIM - QEOS EOS
Phase (rad)
Time (ps)
0
2
4
6
8
10
0
10
20
30
40


Front - Experiment
Back - Experiment
Front - X-RIM - QEOS EOS
Back - X-RIM - QEOS EOS
Front - ESTHER - BLF EOS
Back - ESTHER - BLF EOS
Phase slope ϕ (rad/ps)
Electron temperature T_e (eV)
X-ray Irradiance (10^{15}W/cm^2)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
14
12
10
8
6
4
4.5
5.0
5.5
6.0
6.5


Front - Experiment
Back - Experiment
Front - X-RIM - QEOS EOS
Back - X-RIM - QEOS EOS
Front - ESTHER - BLF EOS
Back - ESTHER - BLF EOS
Phase slope ϕ (rad/ps)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
4.5
5.0
5.5
6.0
X-ray Irradiance (10^15 W/cm^2)
Electron density (m^-3)
10^29
10^28
10^27
-0.8
-0.4
0.0
0.4
x (μm)
Electron temperature (eV)
10
8
6
4
X-RIM - QEOS EOS
1 ps
15 ps
25 ps
35 ps
x(μm)





- ✓ Feasibility - yes
- ✓ Achievable temperature ~ 10 eV
- ✓ Heating uniformity - yes

- X Spatial resolution of the TASRI
- X XFEL spot spatial uniformity

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