4th DyCoMax Workshop – ESRF

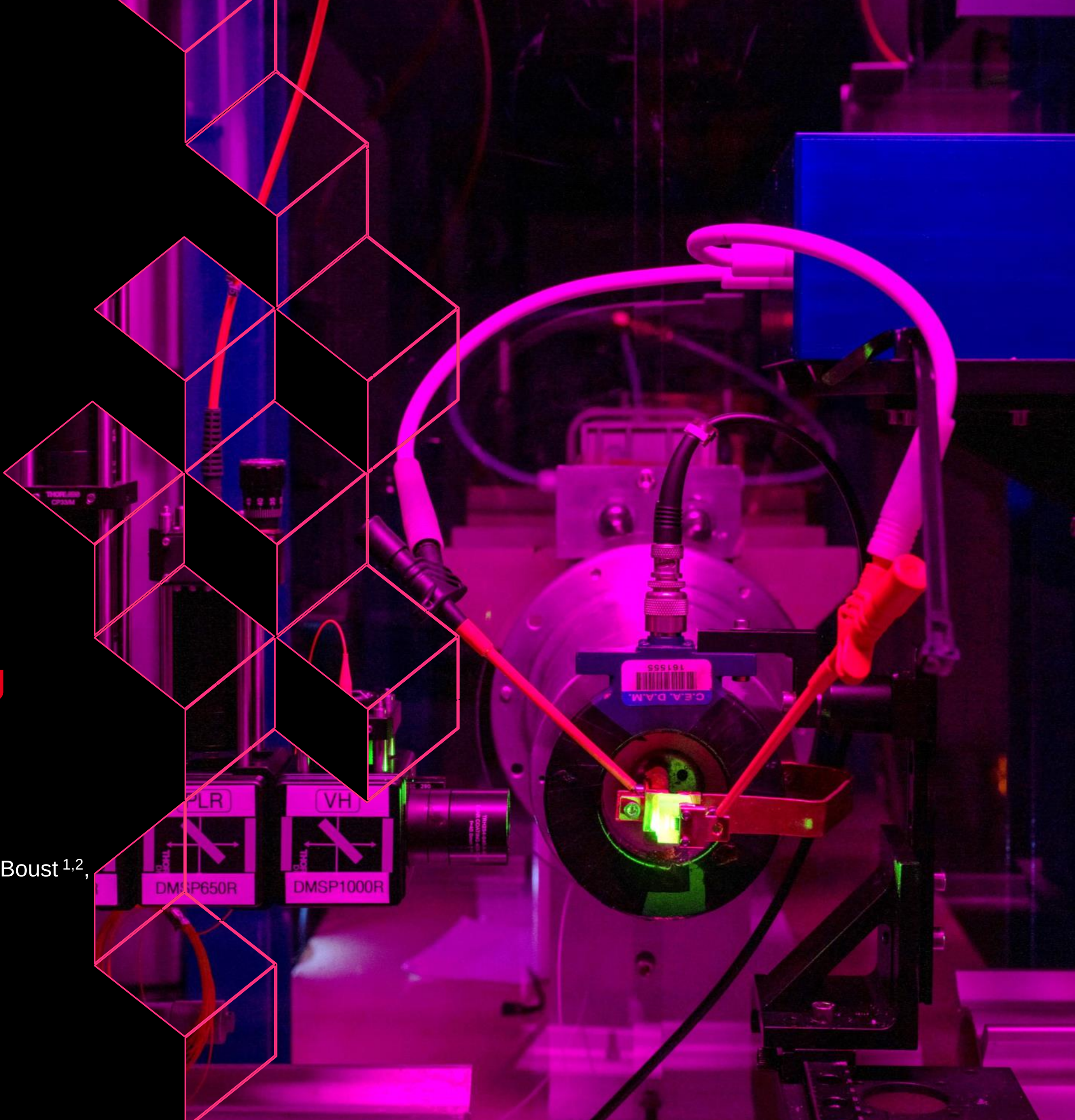
12/03/2024 – 14/03/2024

A pulsed power facility for studying the Warm Dense Matter

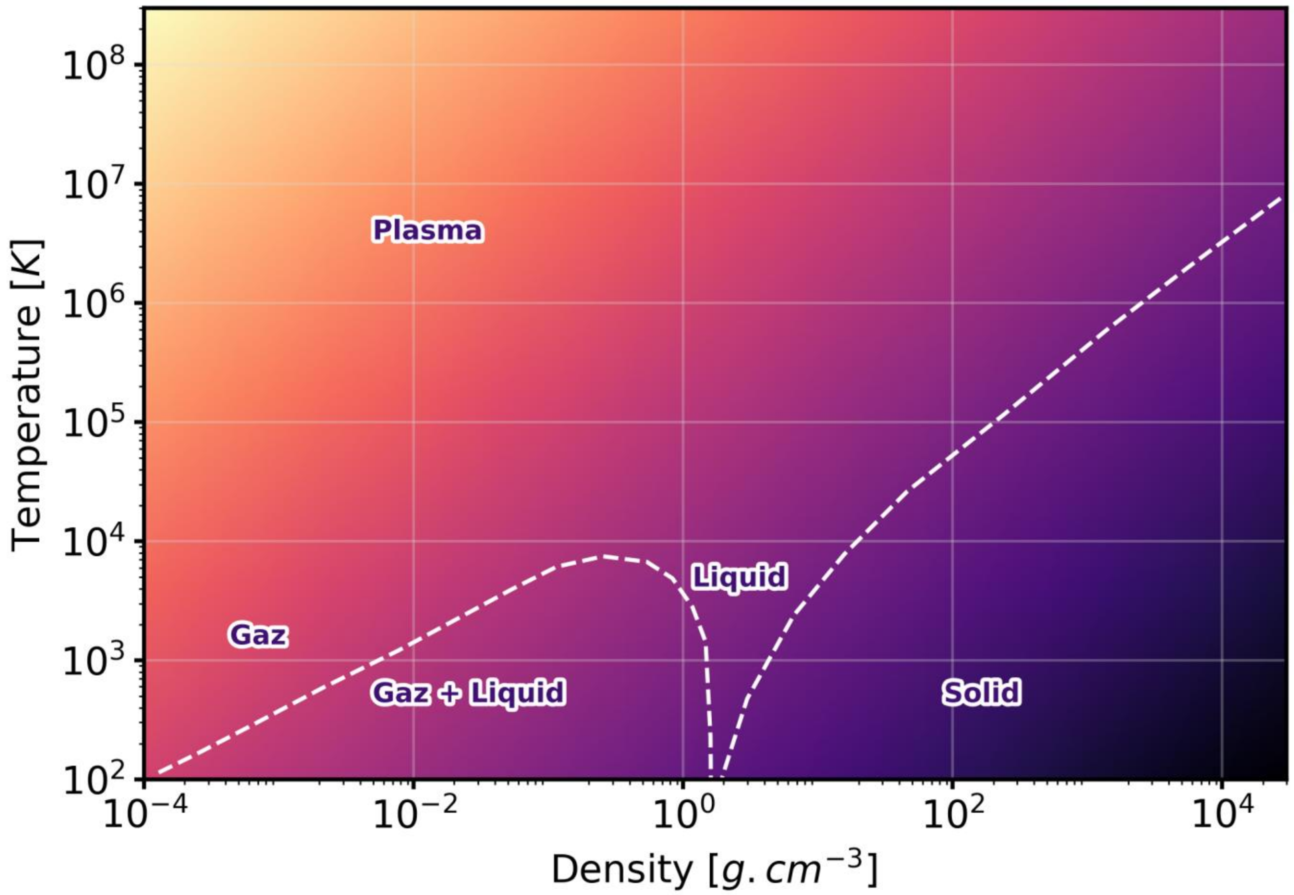
Authors:

B. Jodar [1,2], G. Delachèze-Murel [1,2], J. Auperin [1,2], L. Revello [1,2], F. Brieuc [1,2], J. Boust [1,2], J.-M. Chevalier[3], E. Lescoute[3], C. Blancard [1,2], L. Videau [1,2] and V. Recoules[1,2].

1 – CEA, DAM, DIF, F-91297 Arpajon, France
2 – Université Paris Saclay, CEA, LMCE, F-91680 Bruyères-Le-Châtel, France
3 – CEA CESTA, 15 avenue des sablières, 33116, Le Barp, France



"Warm Dense Matter" ?



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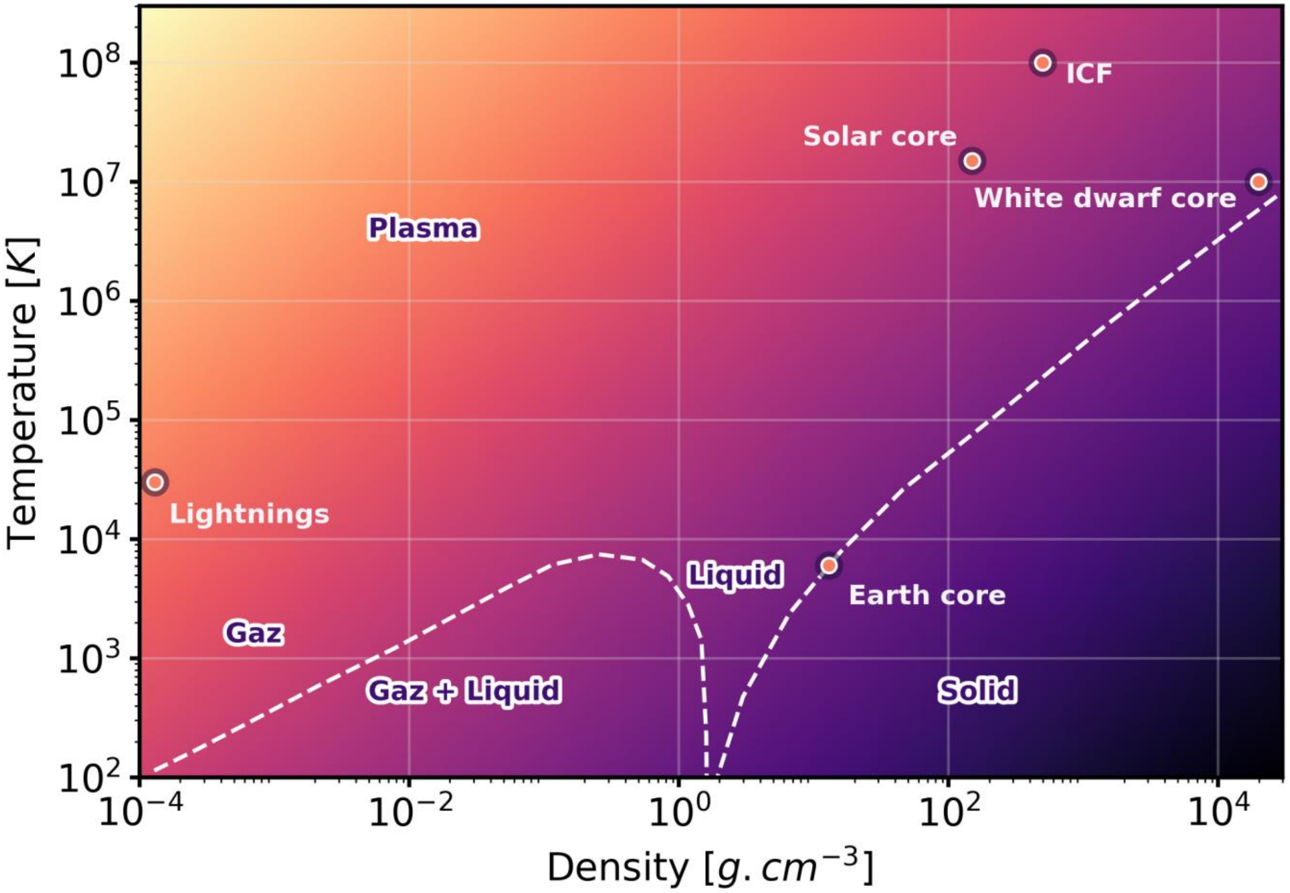

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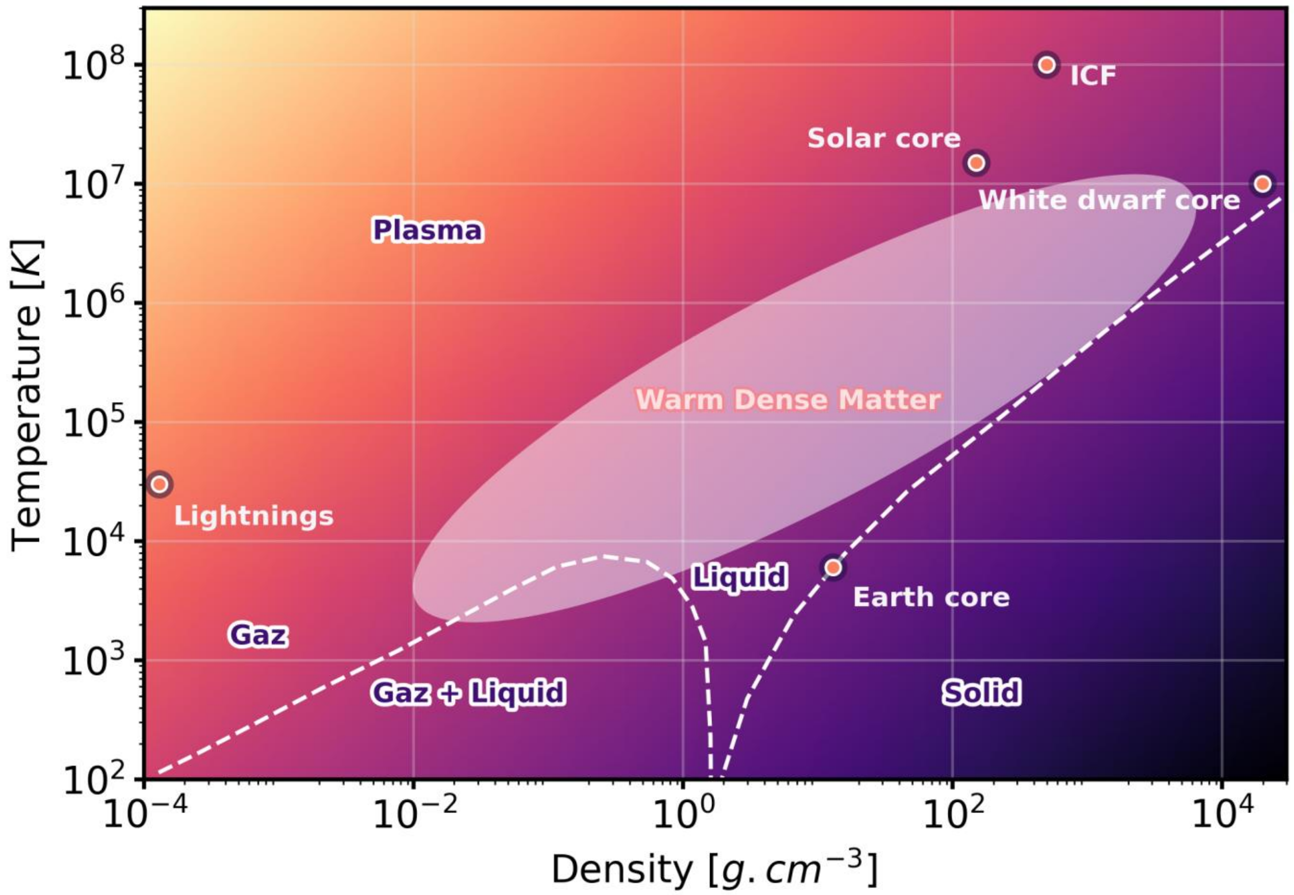

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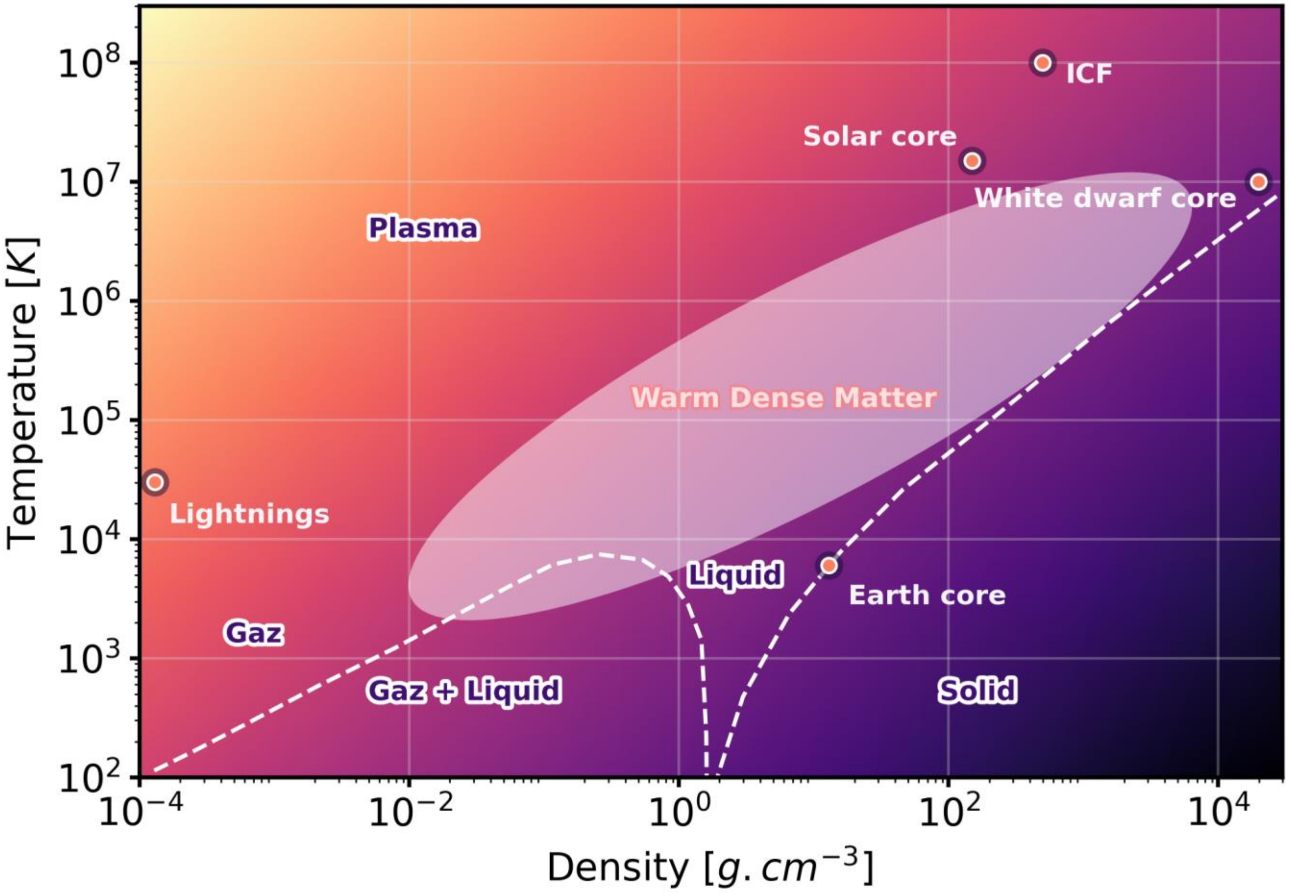

[1] R. W. Lee et al,
« Warm Dense Matter: An Overview »,
LLNL report UCRL-TR-203844

- "From a condensed matter physics perspective, warm dense matter refers to states of matter with solid-like densities and temperatures comparable to TF."

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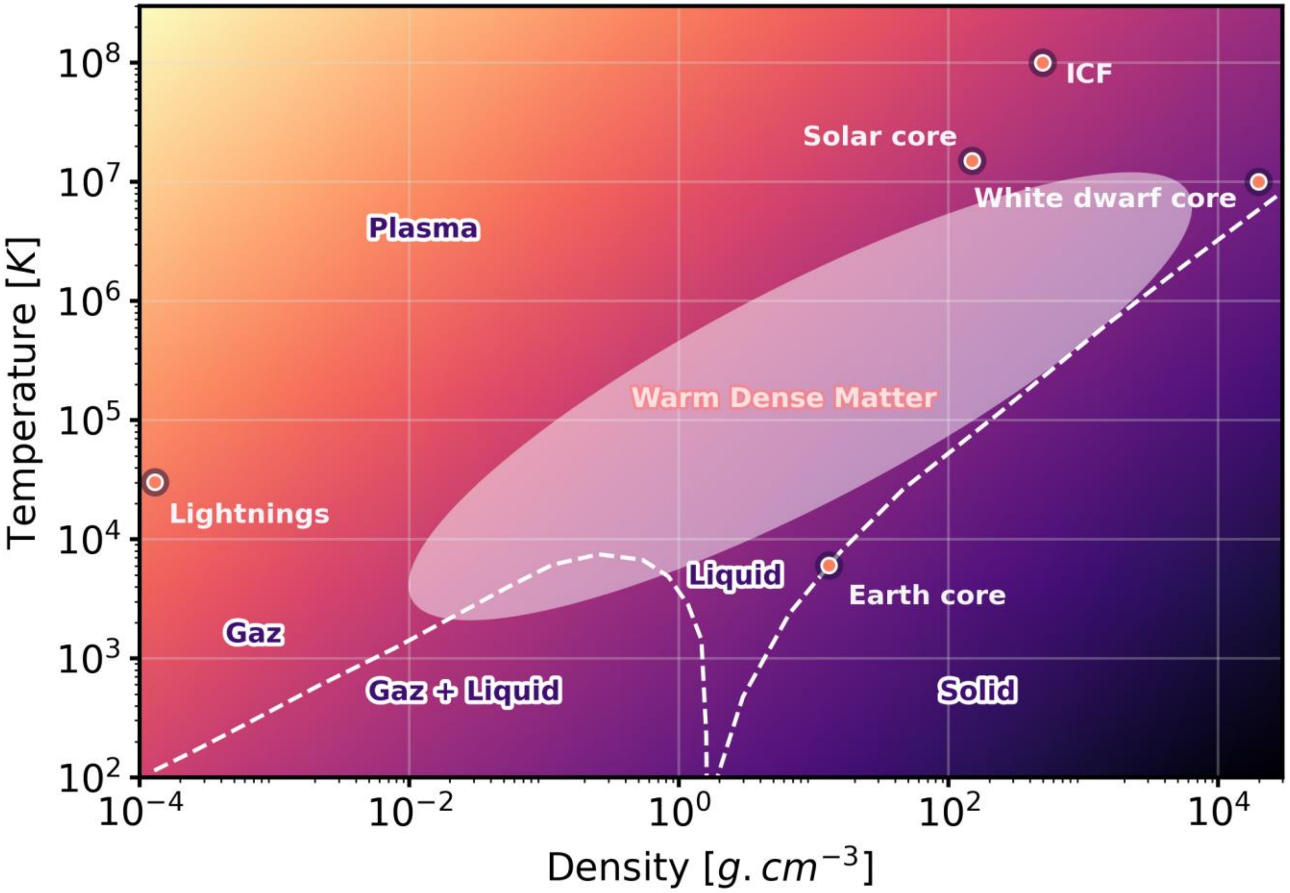

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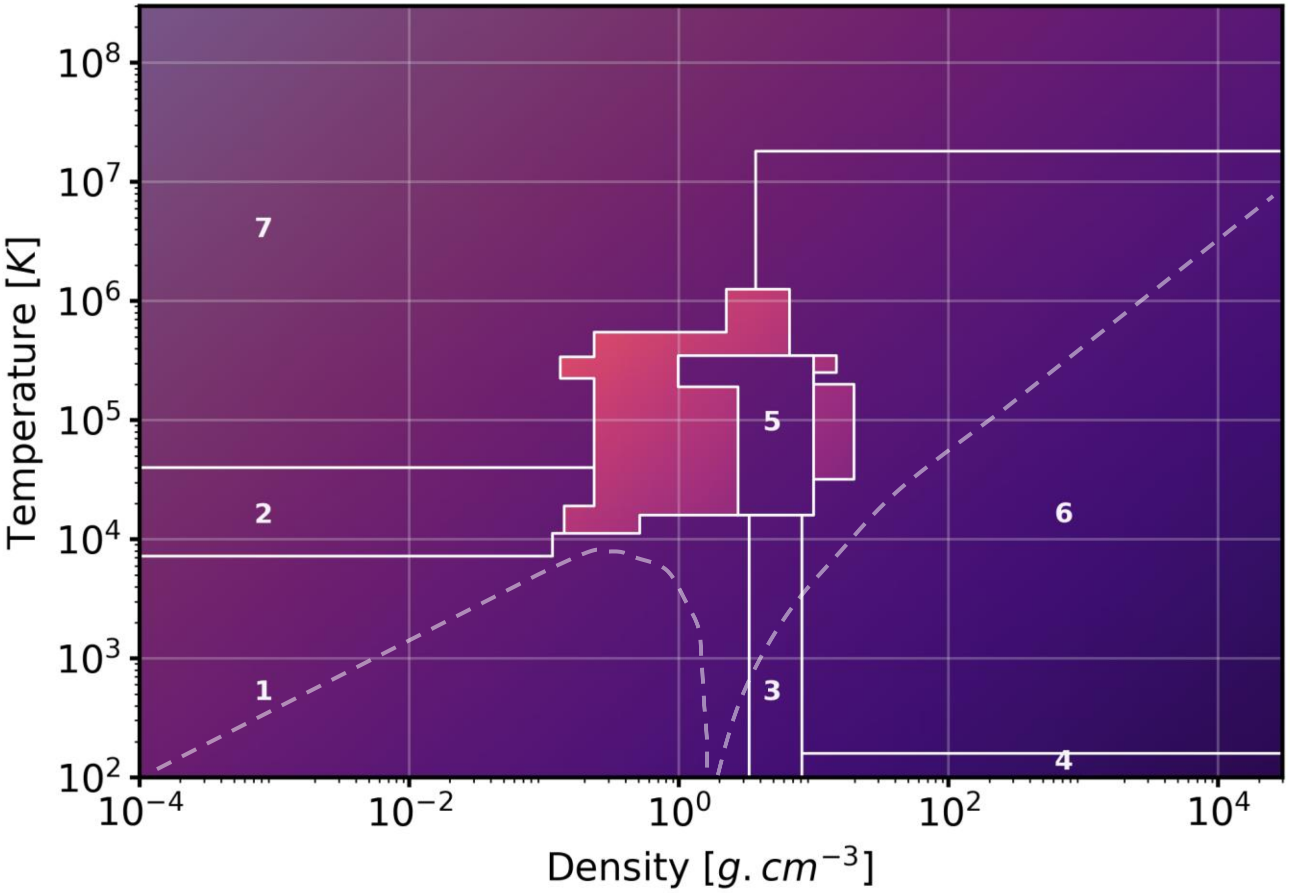
- "From a condensed matter physics perspective, warm dense matter refers to states of matter with solid-like densities and temperatures comparable to TF."
- "From a plasma physics perspective, warm dense matter refers to states of matter that are plasma-like, but that are too dense and/or too cold to be adequately treated by standard plasma physics approaches."

”Warm Dense Matter” ?



1 – Soft sphere model
2 – Saha
3 – Grüneisen-Debye
4 – Augmented Plane waves
5 – Perturbation theory applied to liquid metal
6 – Thomas-Fermi
7 – ACTEX

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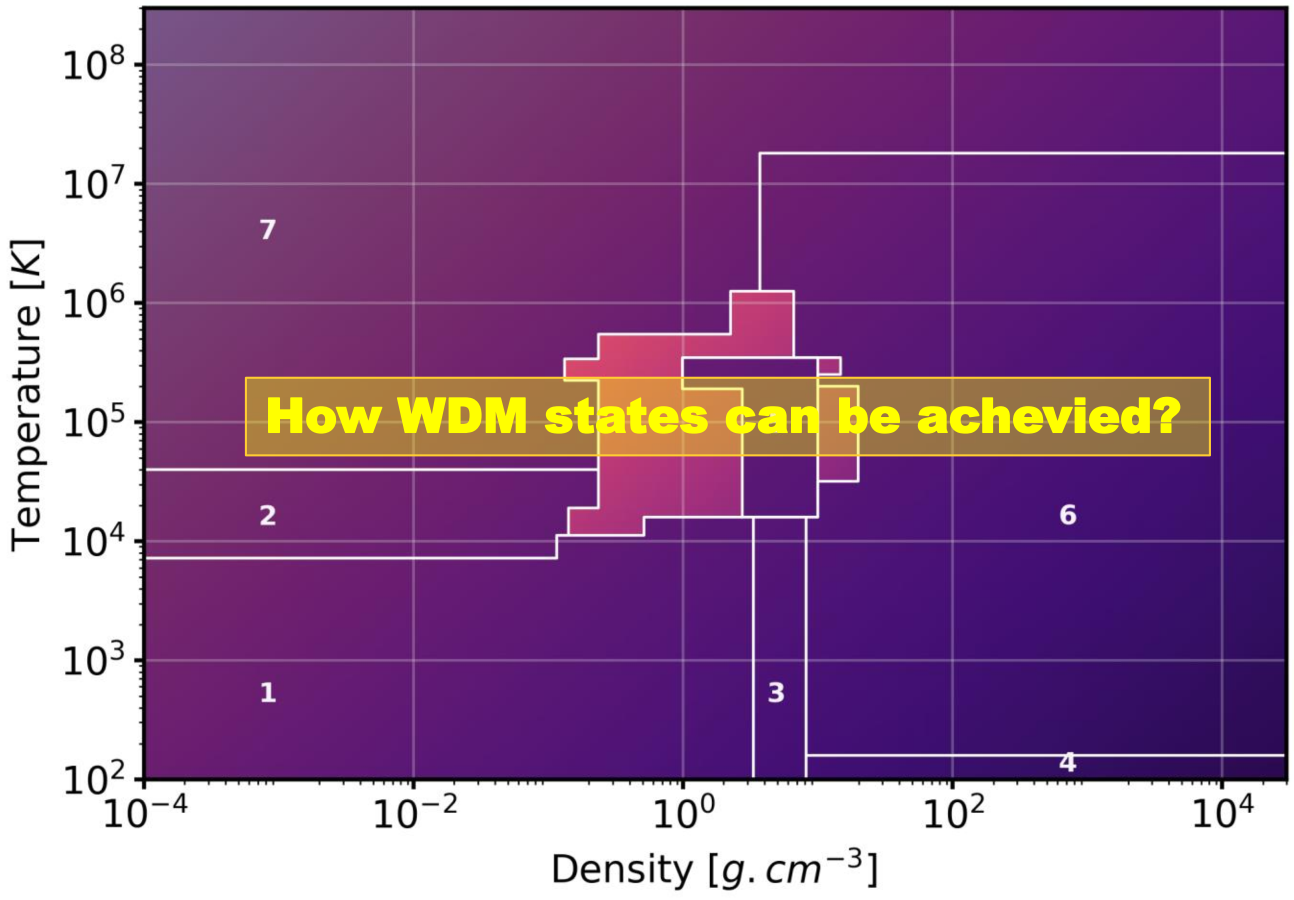

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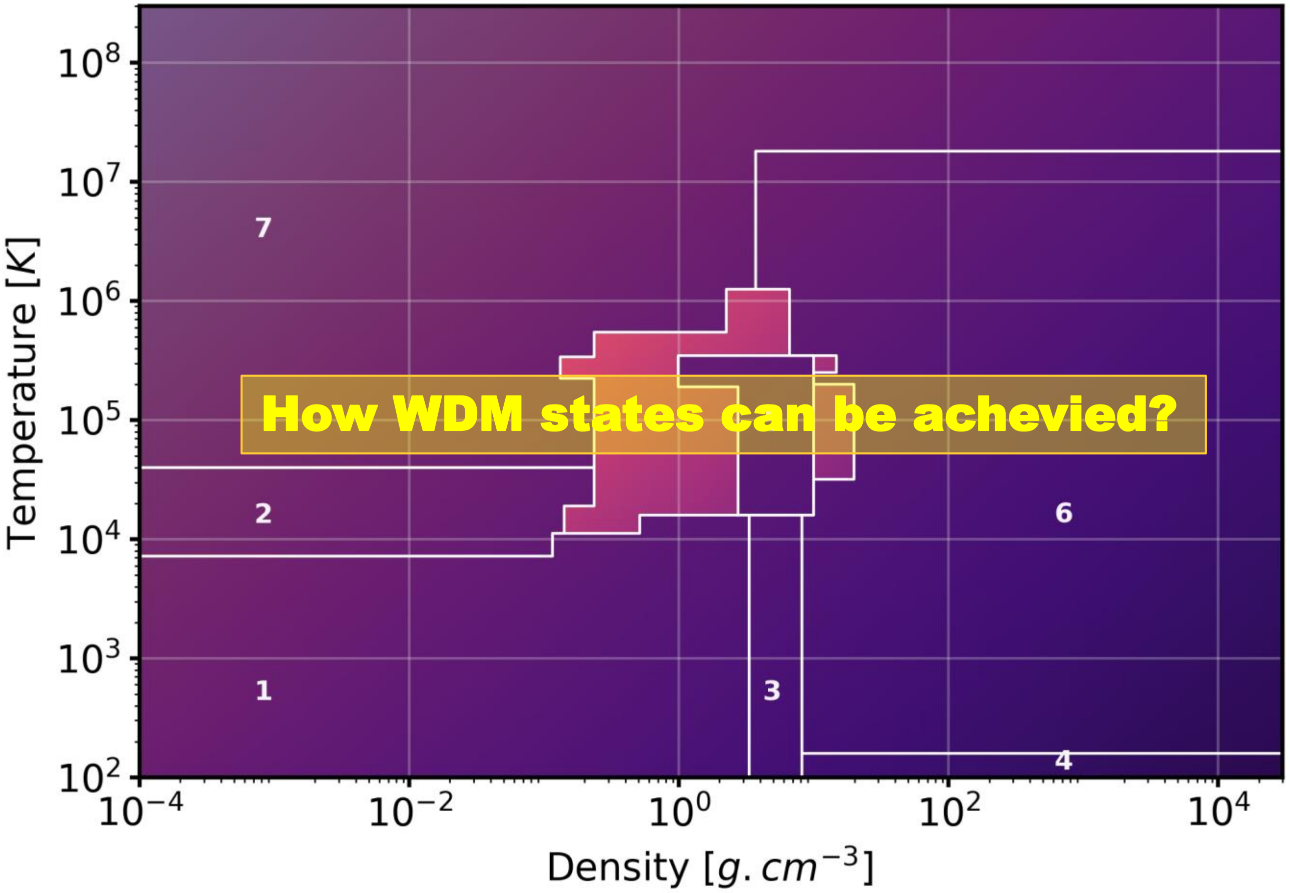

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Beam sources

- Heavy Ion beams
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- Relativistic electron beams
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- Proton beams
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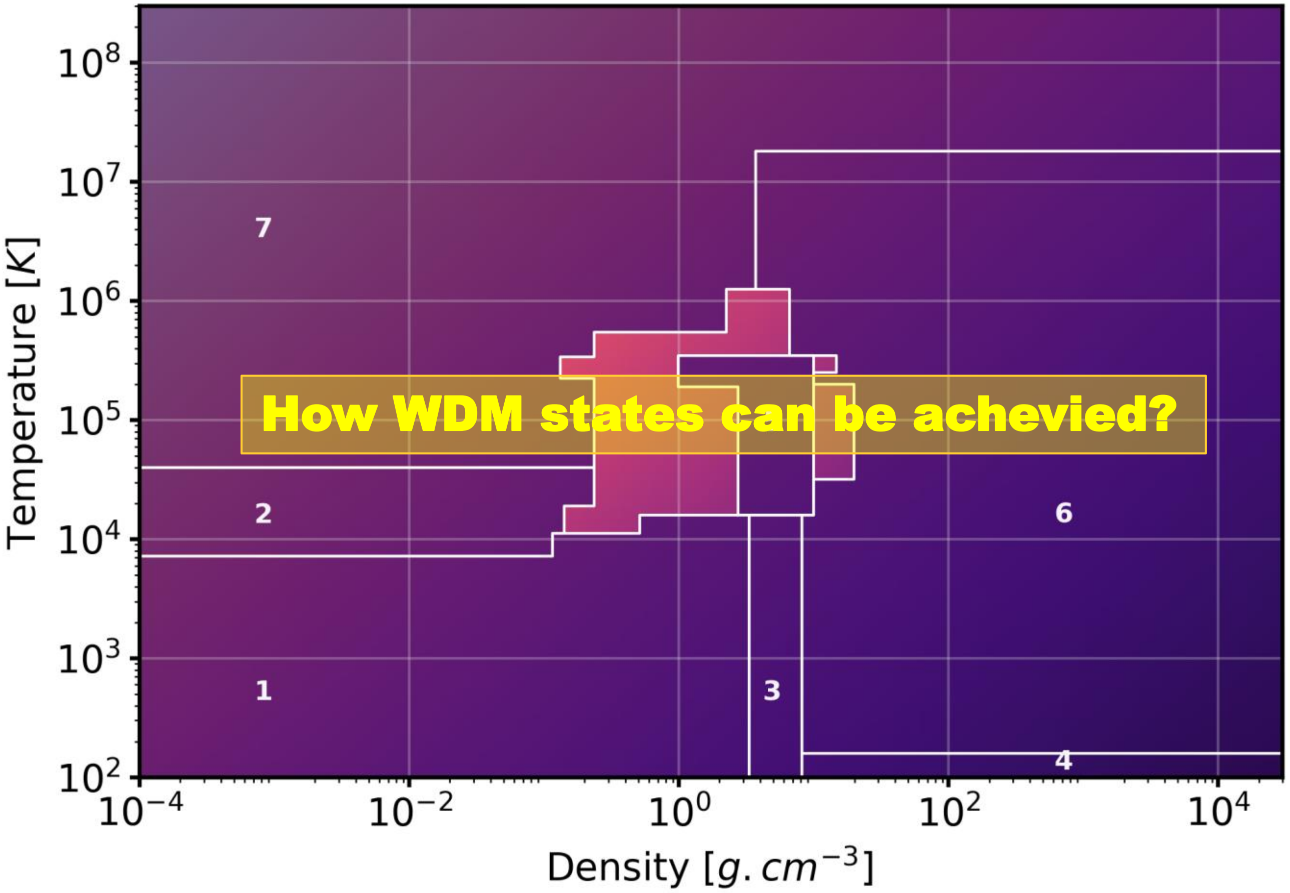

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Lasers

- ❑ Ultra High-Intensity Lasers
[5] M. Ishino et al, J. Appl. Phys. 116, 183302 (2014)
- ❑ Intense shock waves generation
[6] A. Benuzzi-Mounaix et al, PRL 107, 165006 (2011)
- ❑ Quasi-isentropic ramp compression
[7] J.-P. Davis et al, J. Appl. Phys. 99, 103512 (2006)

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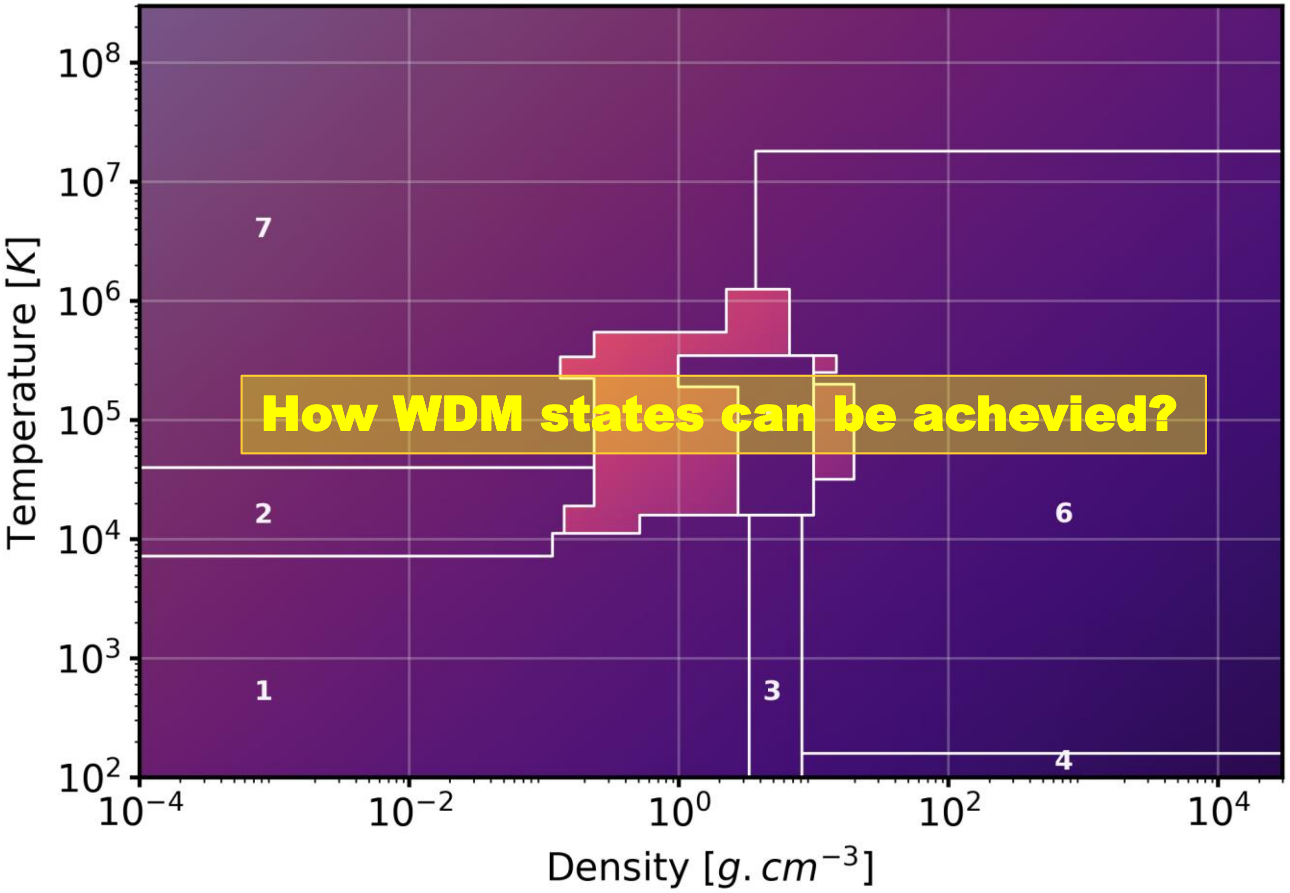

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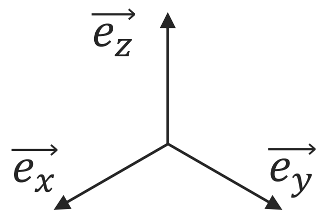
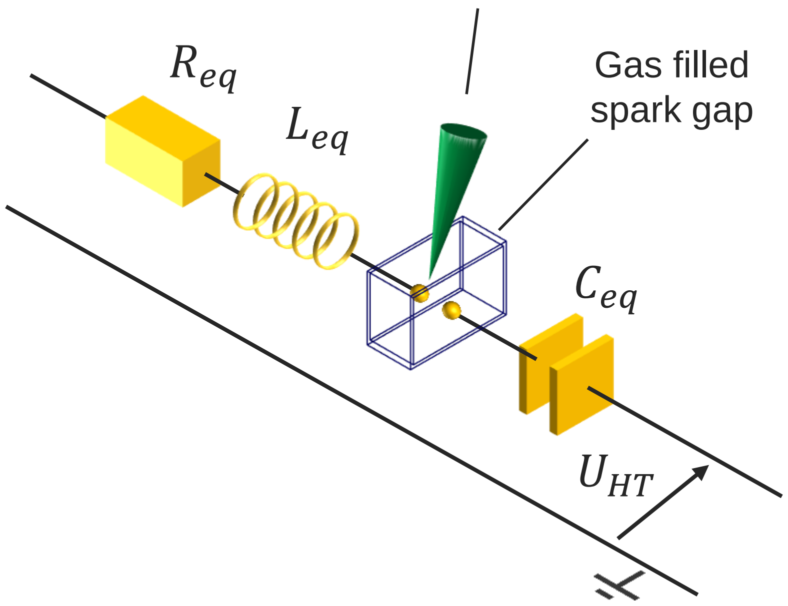
Electrical Current Pulse

[8] G. R. Gathers, Int. J. Thermophys. 4, **209** (1983)

Experimental Set-up



U_{HT}	$20\ \ldots 50\ kV$
R_{eq}	$0.35\ \Omega$
L_{eq}	$180\ nH$
C_{eq}	$3.96\ \mu F$
τ_{rising}	$\approx 1\ \mu s$



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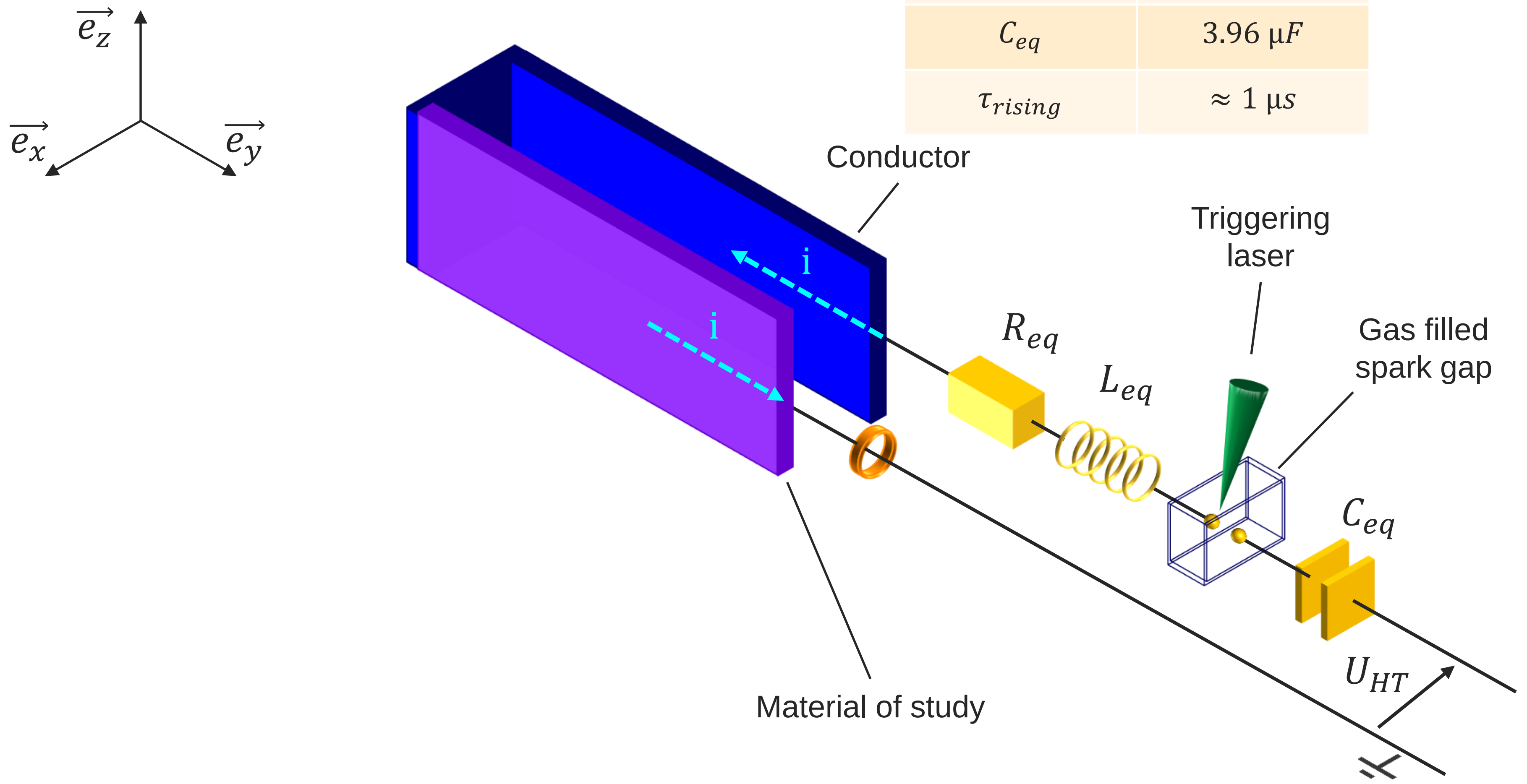

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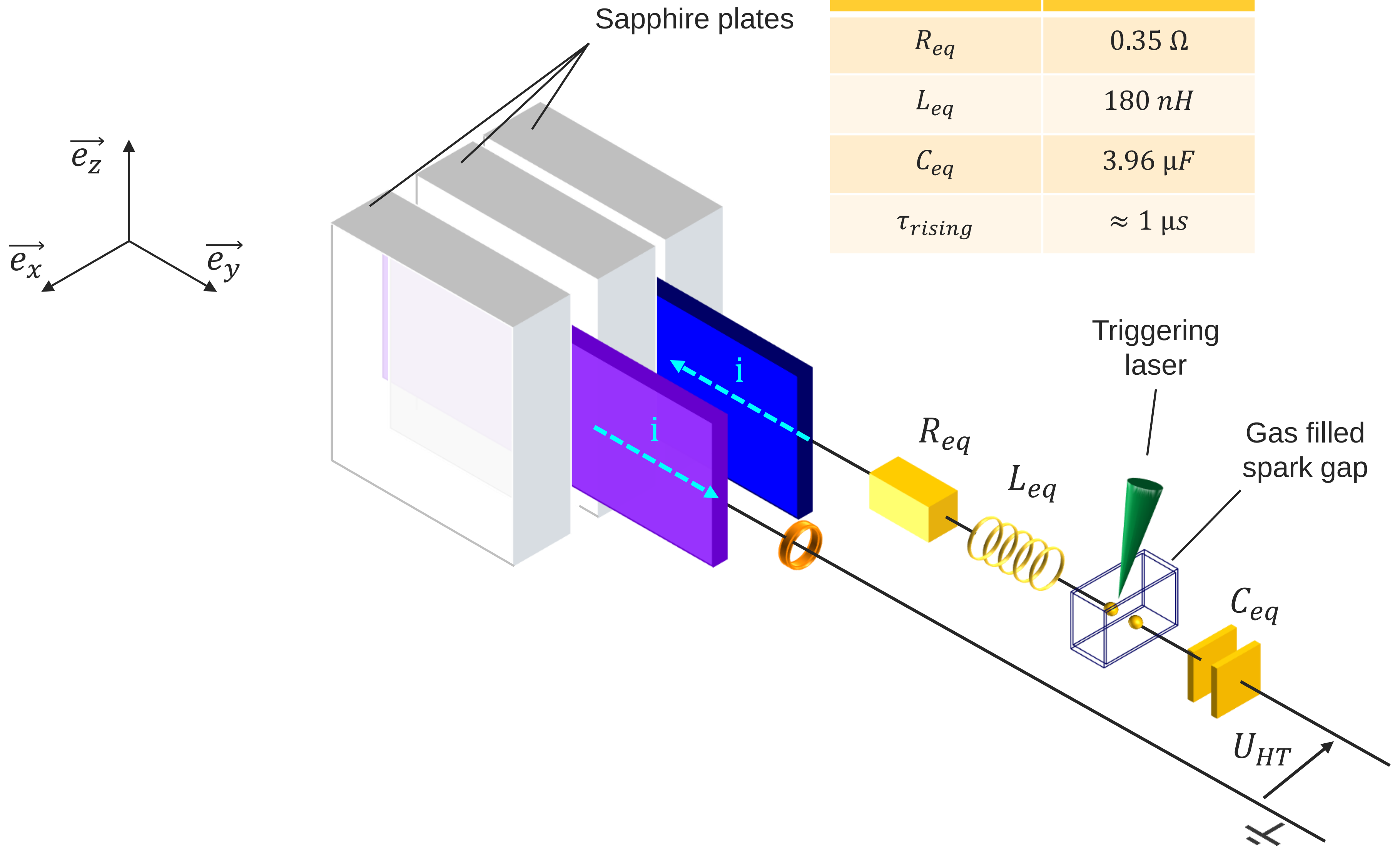

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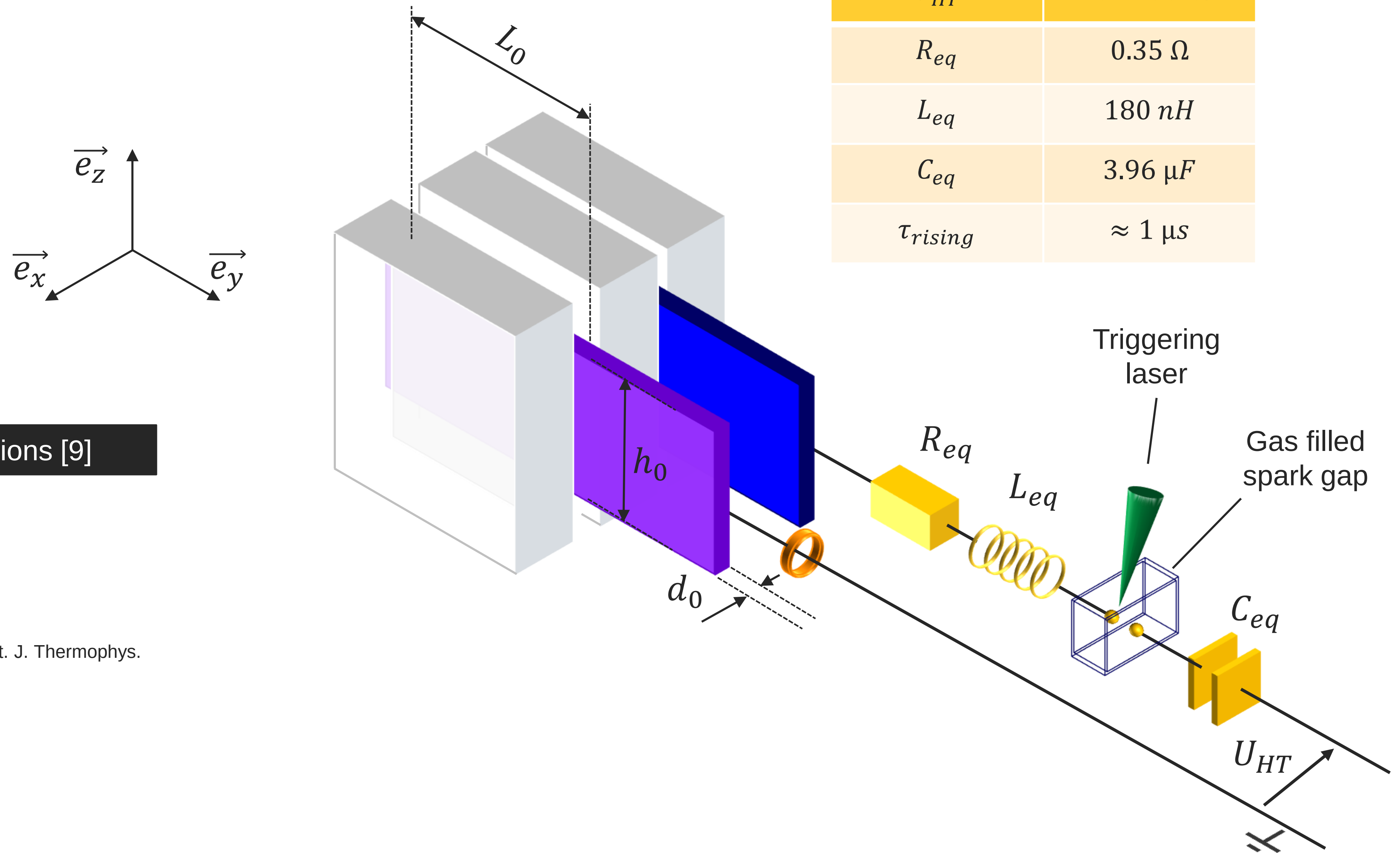

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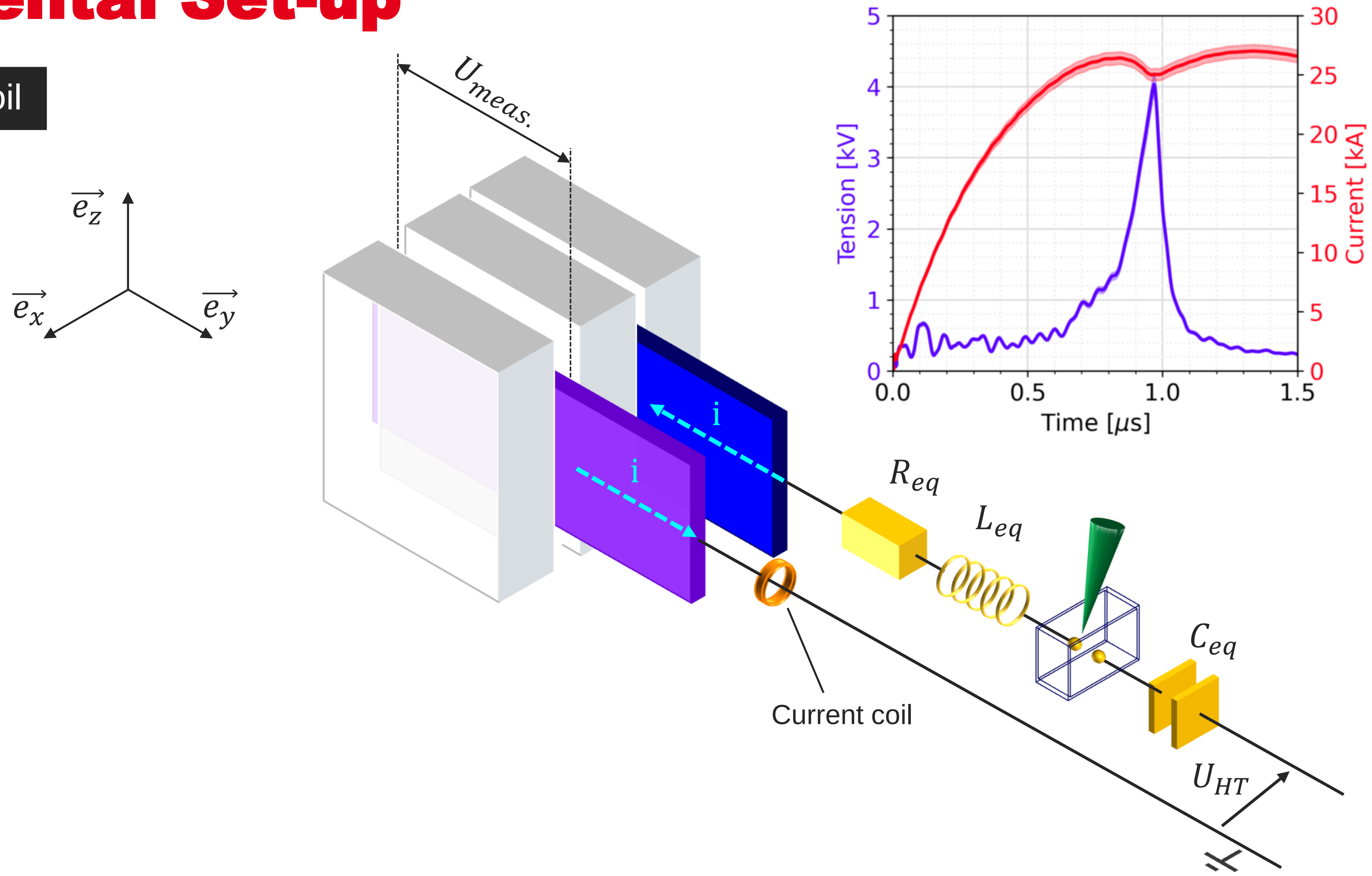
Uniform heating conditions [9]

- ❑ $\tau_{rising} \leq 1\ \mu s$
- ❑ $(L_0\ \&\ h_0) \gg d_0$
- ❑ Inertial confinement
  →1D displacement

[9] V. N. Korobenko and A. D. Rakhel, Int. J. Thermophys. **20**, (1999).

Experimental Set-up

Al | 12 µm thick foil



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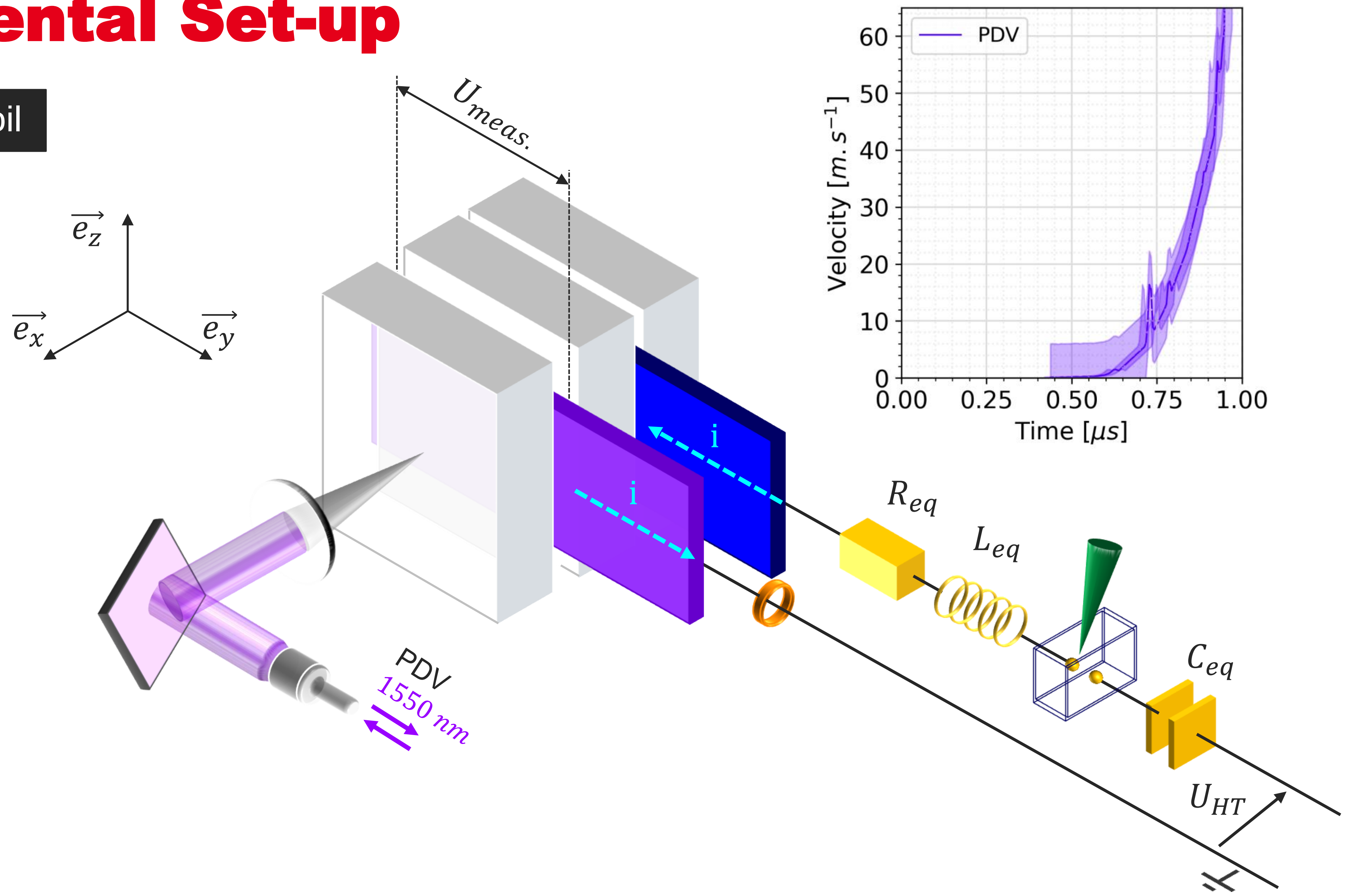

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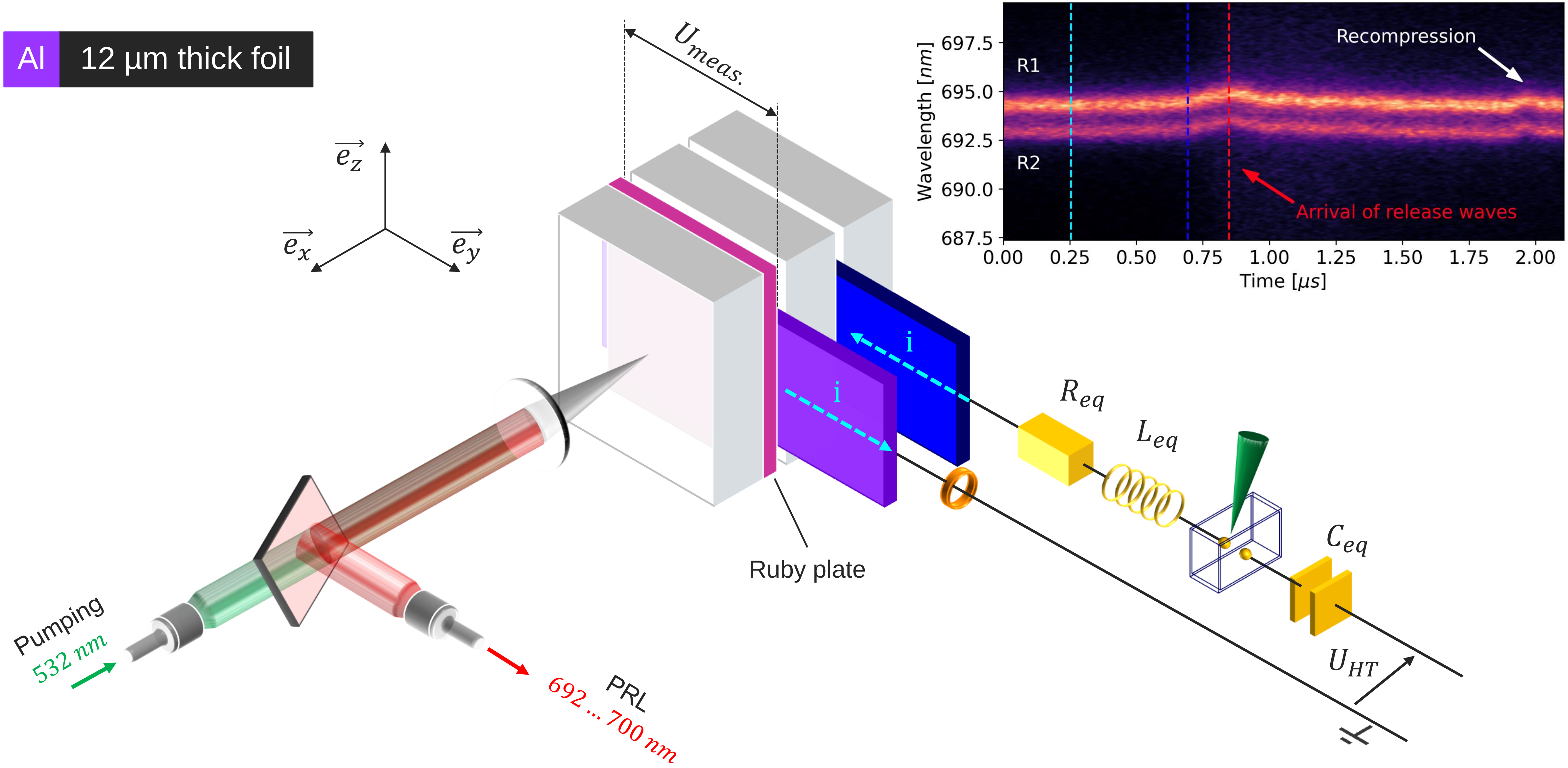

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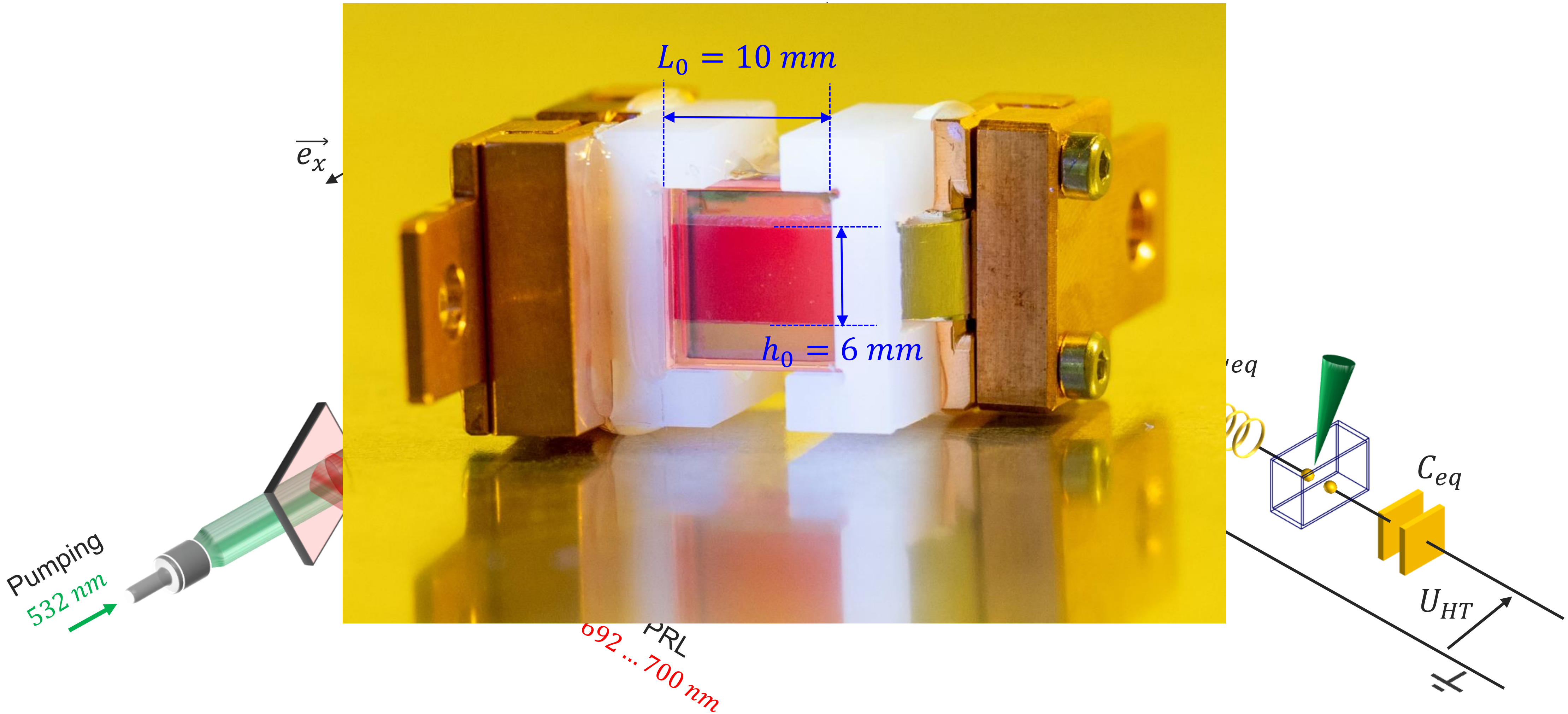

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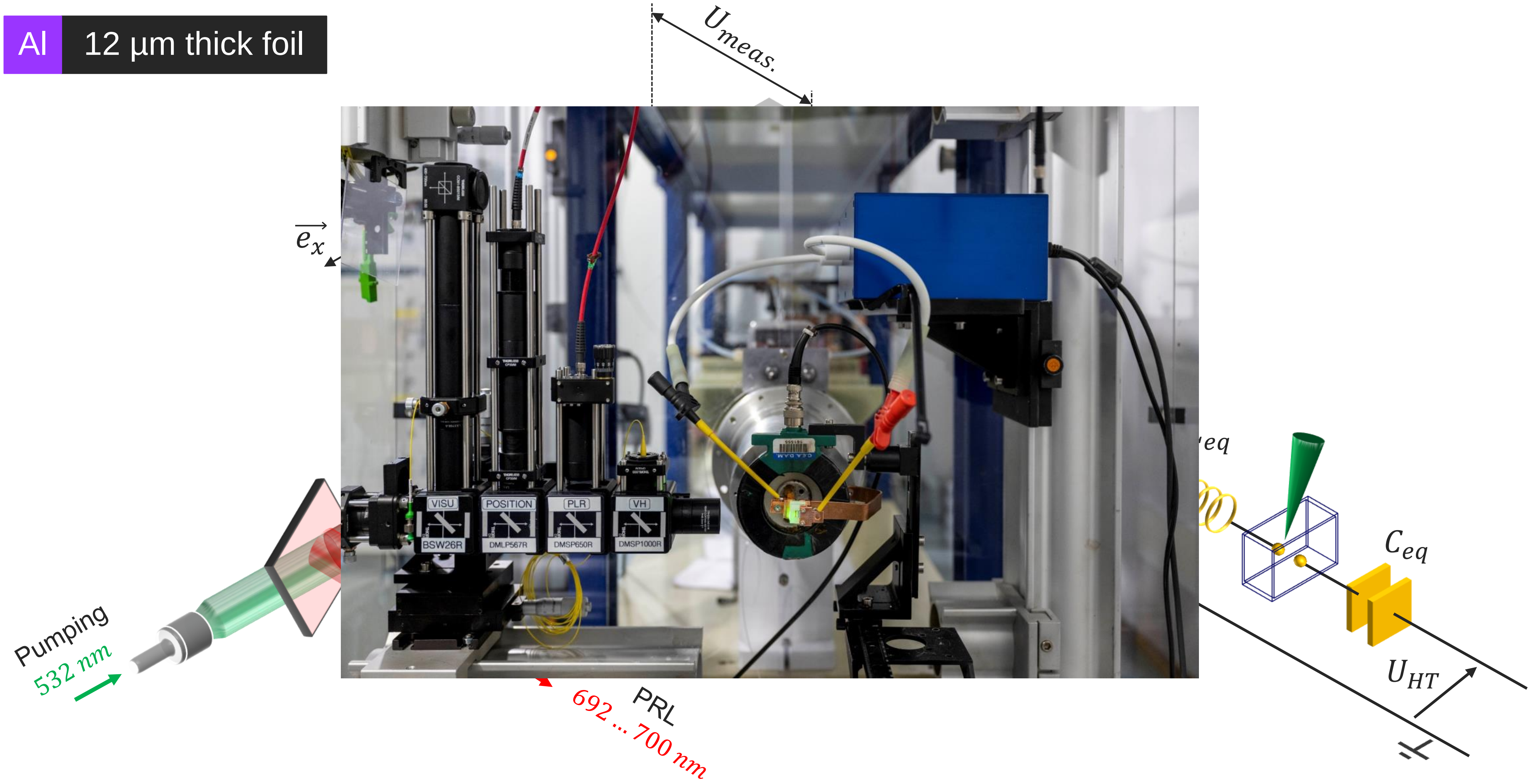
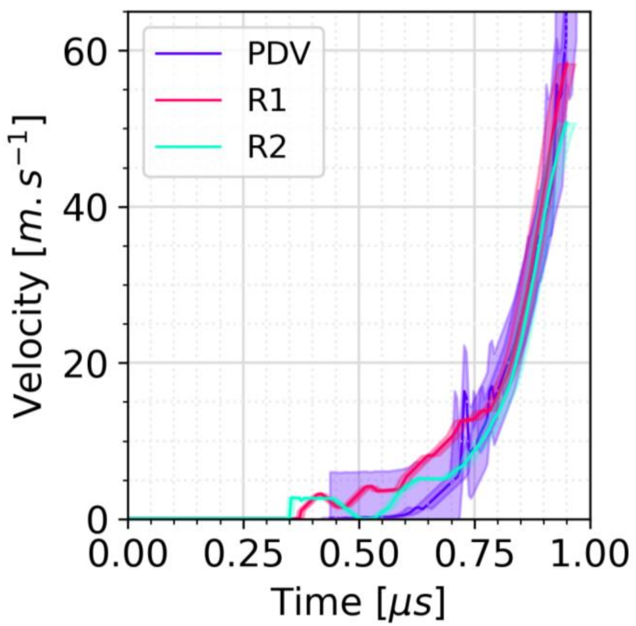


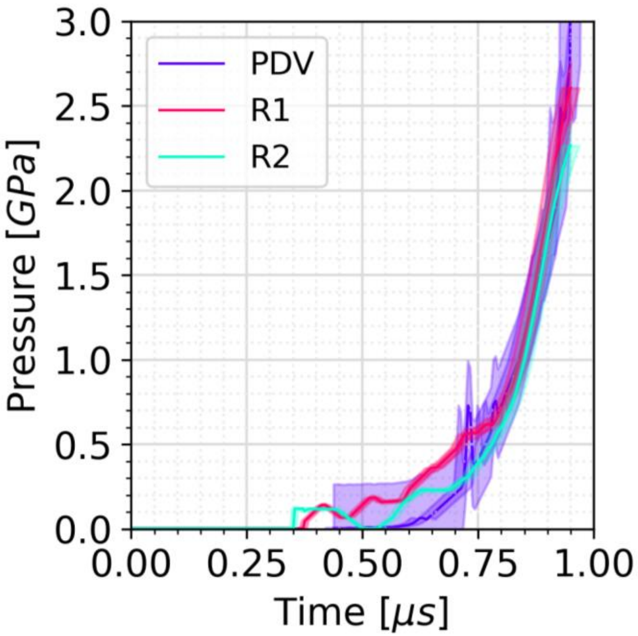
Experimental data

Equation of State | Al

- **Sapphire adiabatic EOS** [10] :
  - Uni-axial displacement
  - $P = \frac{C_{11}^S}{n}\left[\left(\frac{\rho_0}{\rho}\right)^n - 1\right] \rightarrow P(t) = \frac{C_{11}^S}{n}\left[\left(\frac{n-1}{2c}U_p(t) + 1\right)^{\frac{2n}{n-1}} - 1\right]$

- **Application to direct measurements:**
  - $P^{PDV}(t) = \frac{C_{11}^S}{n}\left[\left(\frac{n-1}{2c}U_p^{PDV}(t) + 1\right)^{\frac{2n}{n-1}} - 1\right]$
  - $U^{R1}(t) = \frac{2c}{n}\left[\left(\frac{n}{C_{11}^S}P^{R1}(t) + 1\right)^{\frac{n-1}{2n}} - 1\right]$
  - $U^{R2}(t) = \frac{2c}{n}\left[\left(\frac{n}{C_{11}^S}P^{R2}(t) + 1\right)^{\frac{n-1}{2n}} - 1\right]$





[10] V.N. Korobenko and A.D. Rahkel. Phys. Rev. B **75,** 064208 (2007).

Experimental data

Equation of State | Al

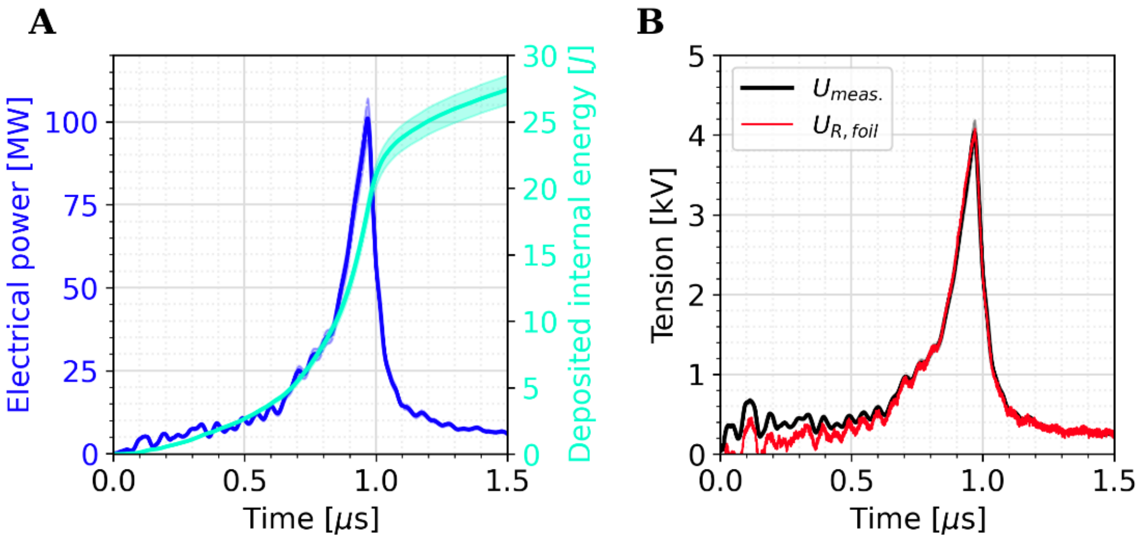
- **Internal energy variation:**
  - Tension correction

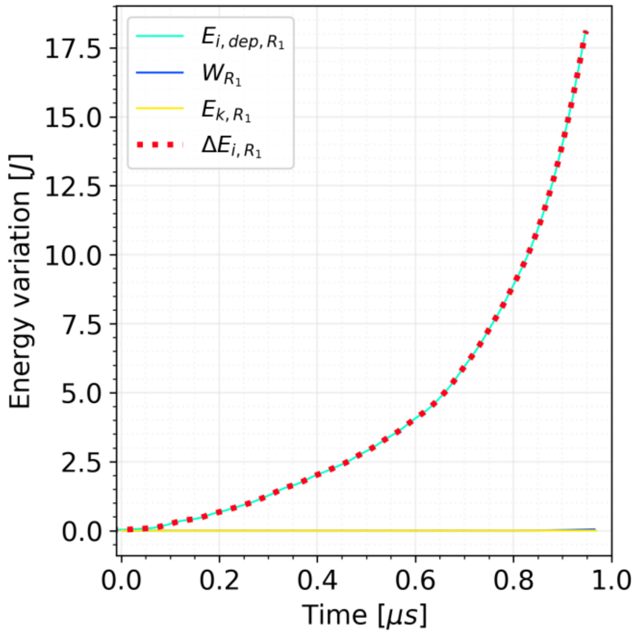
$$\rightarrow U_{R,foil}(t) = U_{meas.}(t) - L_{0,foil} \cdot \frac{dI}{dt}$$

  - Deposited internal energy

$$\rightarrow E_{i,dep}(t) = \int U_{R,foil} . I . dt$$

  - $\Delta E_i = E_{i,dep} - P(t)dV(t) - \frac{1}{2} m_0 U_p^2$





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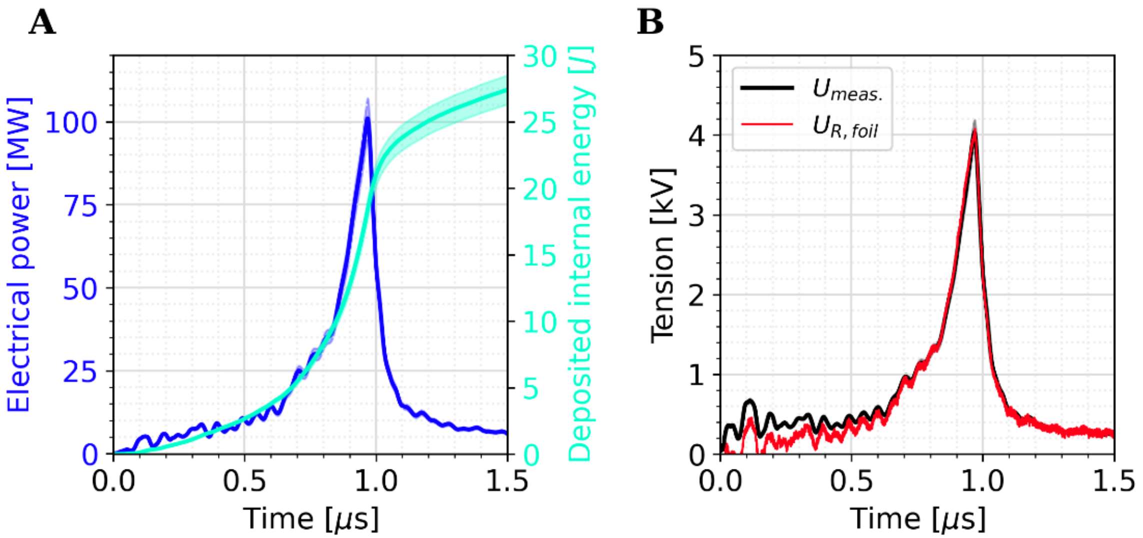
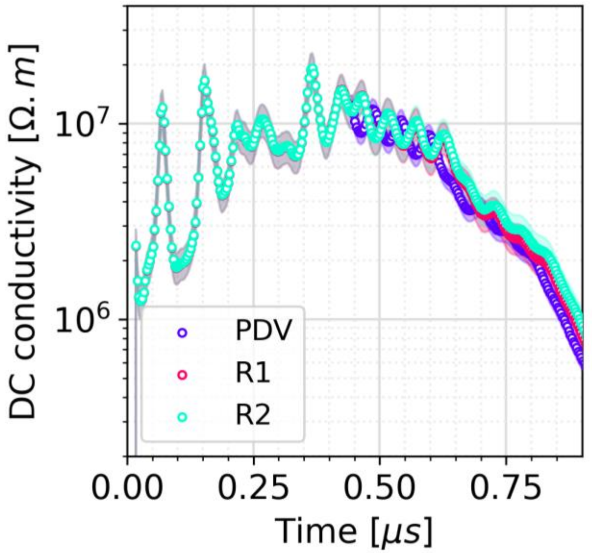
- **Density :**
  - Uni-axial displacement

$$\rightarrow \rho(t) = \frac{m_0}{l_0h_0d_0} \cdot \frac{1}{(1+\frac{2}{d_0}\int U_p.dt)}$$

- **DC conductivity :**
  - $\sigma_e(t) = \frac{l_0^2\rho(t)}{m_0} \cdot \frac{I(t)}{U_{R,foil}(t)}$





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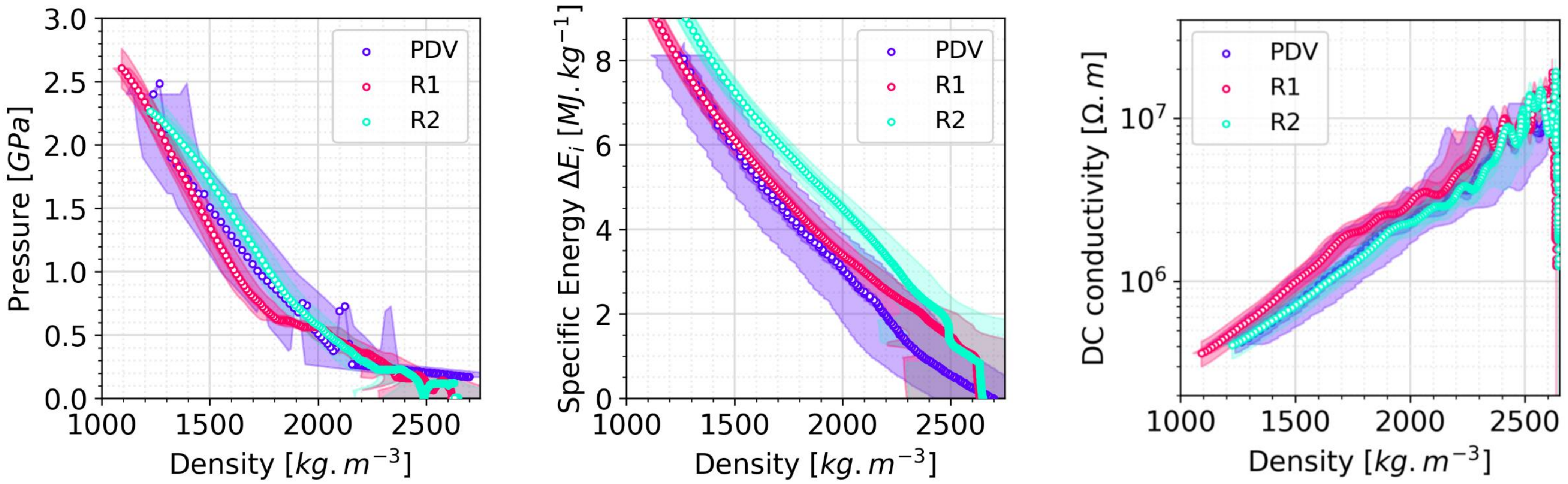
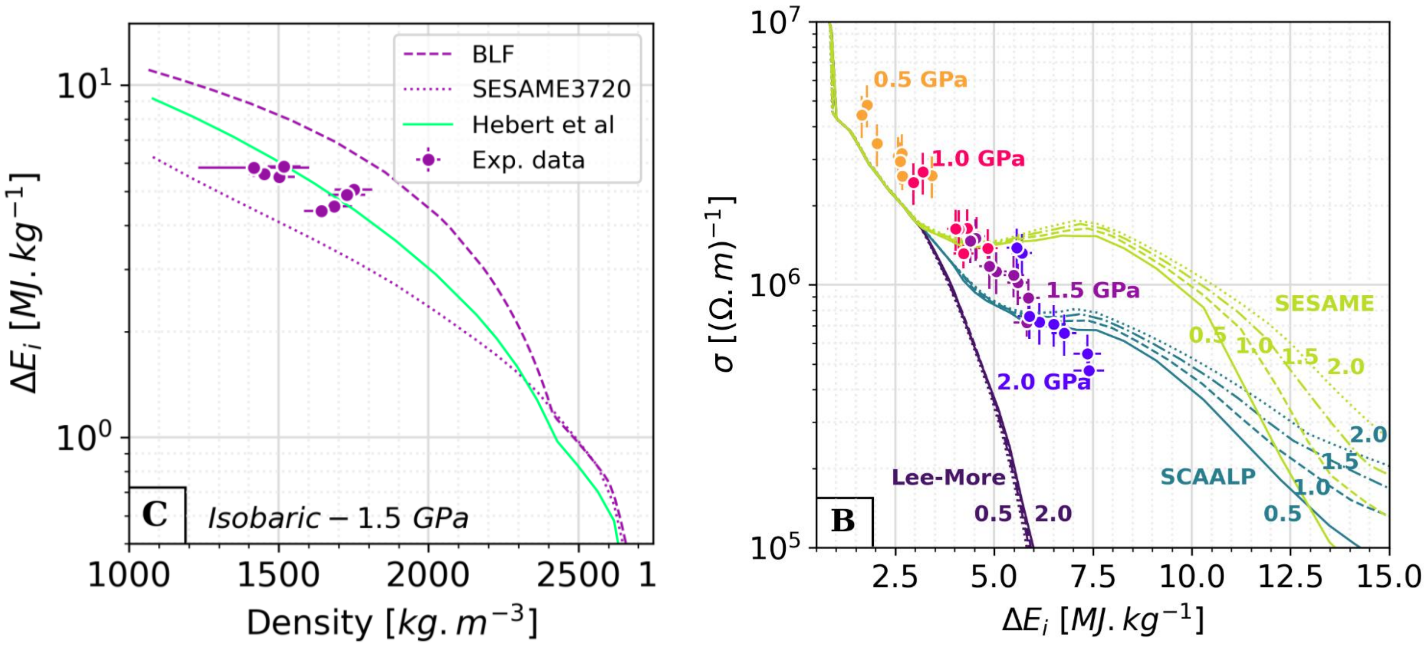


- Consistency of collected data with PRL and PDV diagnostics during one discharge
- Work in progress for reducing uncertainties at discharge first stages

Simulations

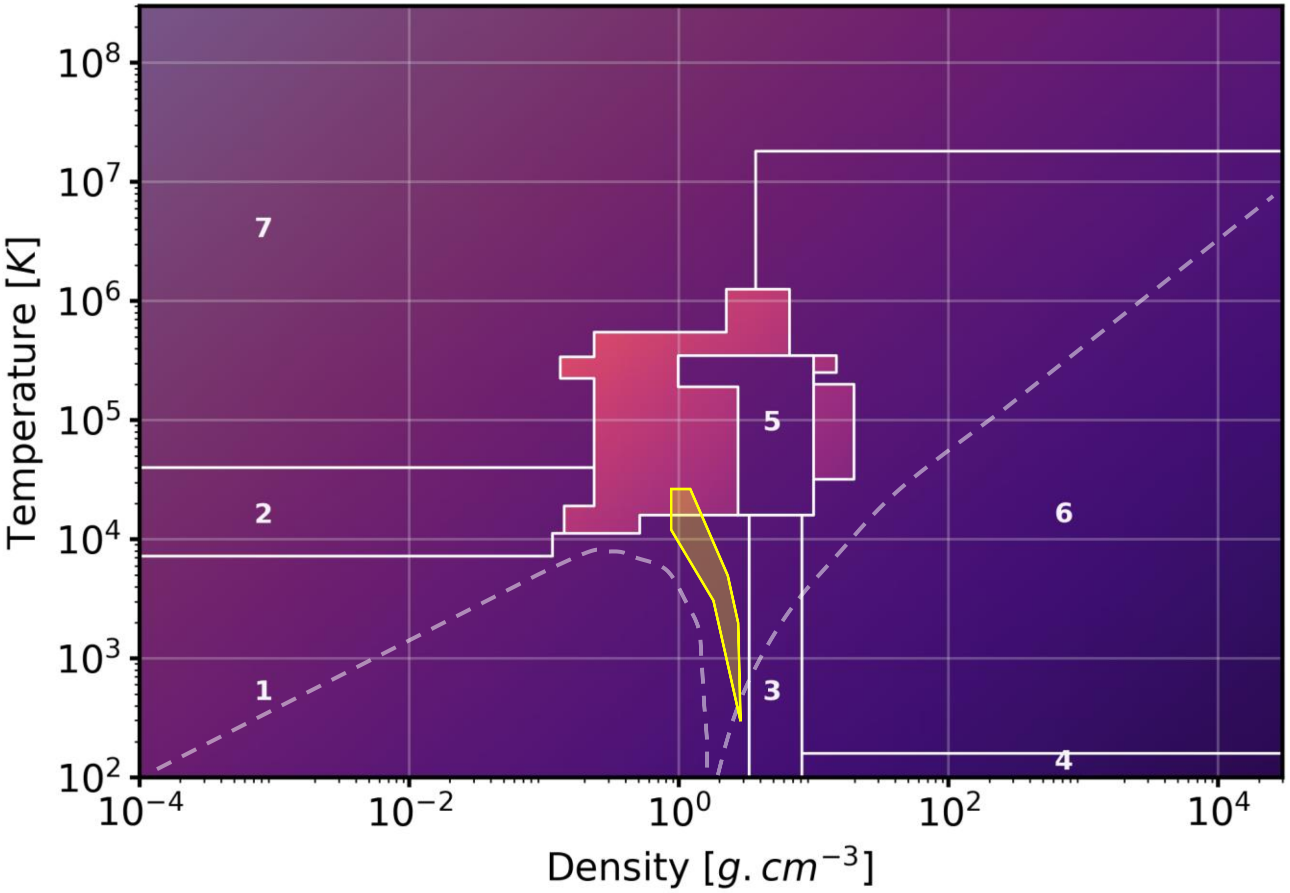
Ab Init | Al

- Quantum Molecular Dynamic simulations on aluminum
- Comparison to EOSs [11-13] and conductivity models [14-15]



[11] S.P. Lyon and J. D. Johnson. SESAME: The Los Alamos national laboratory equation of state database. LANL LA-UR-92-3407, 1992.
[12] A.V. Bushman, I.V. Lomonosov and V.E. Fortov, Russian Academy of Sciences, Chernogolovka, 1987.
[13] D. Hébert et al., J. Appl. Phys. **133** (125901) 2023.
[14] Y. T. Lee and R. M. More, Phys. Fluids **27** (5), 1273-1286 (1984).
[15] G. Faussurier et al., Phys. Plasmas **17** (5), 052707 (2010).

Where are we?



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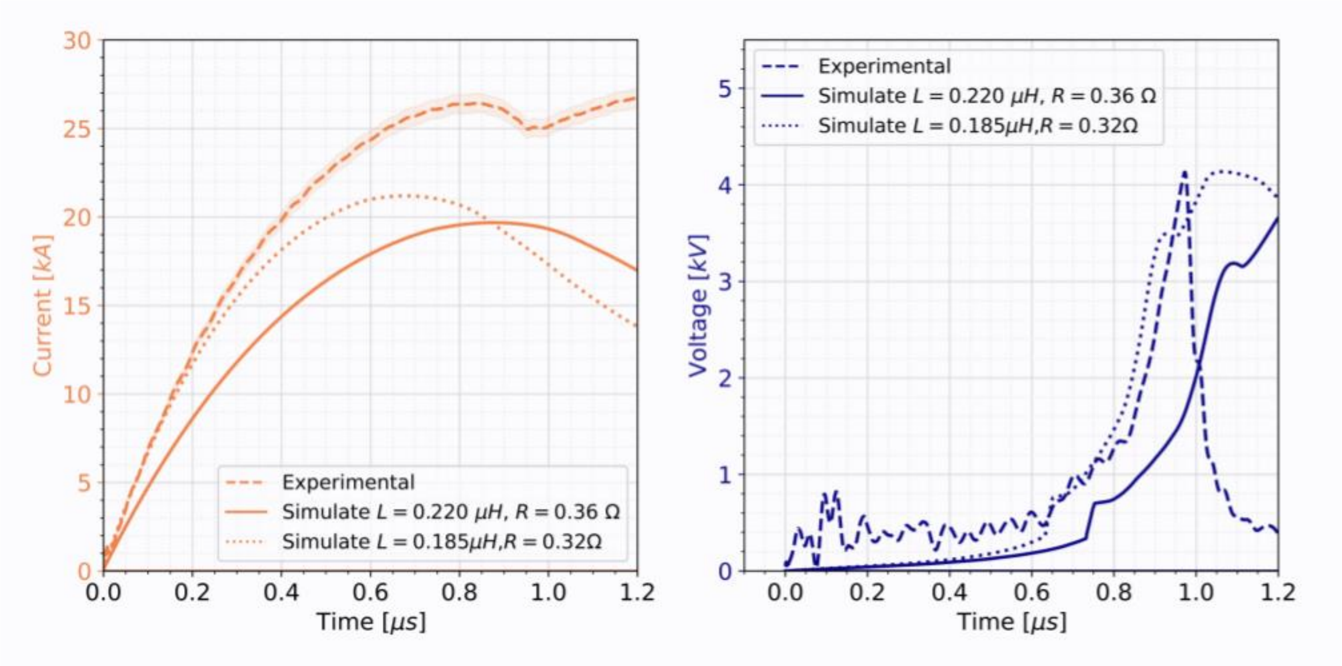
What's next?

- 1D lagrangian hydrodynamic simulations using ESTHER [17] → **See L. Revello's poster!!**

  [16] S. Bardy et al, Opt. & Laser Tech., **124** 105983 (2020).



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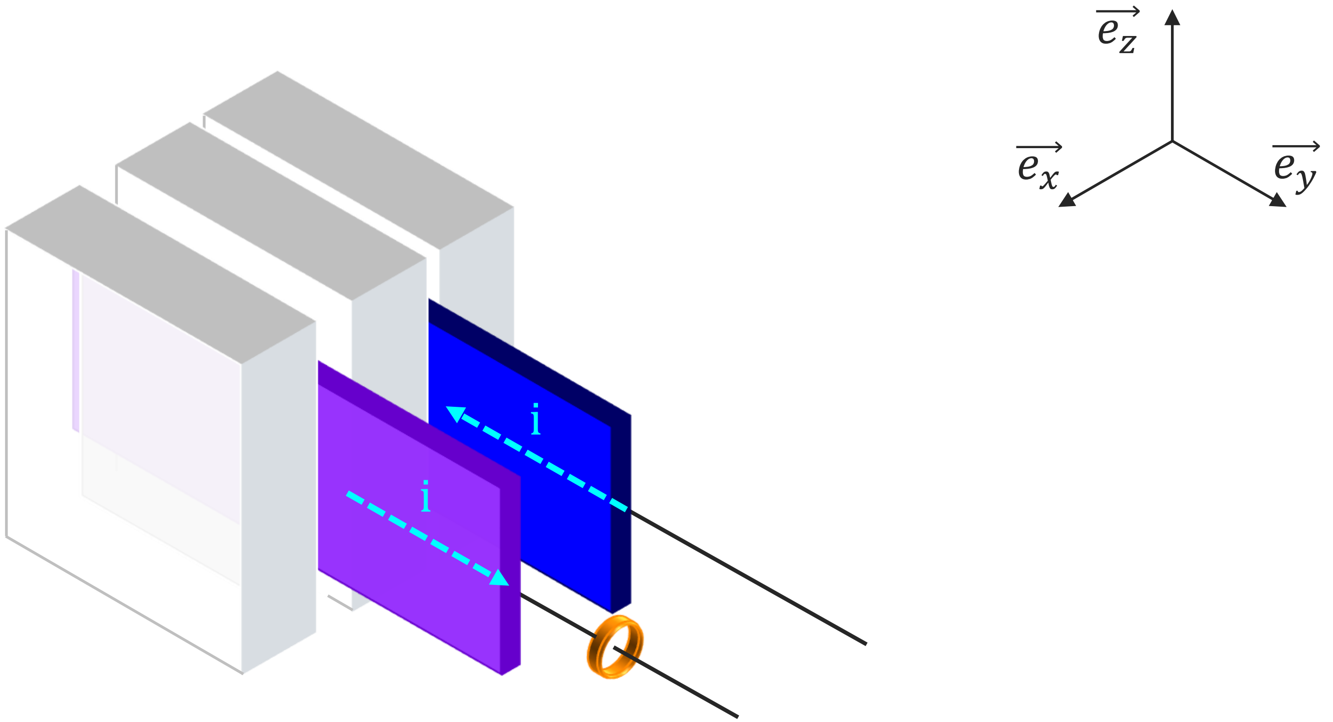
- Experiments on **Cu** → **XAS experiment proposal on ID24 HPLA** (collab. with J. Strucka & S. Bland)



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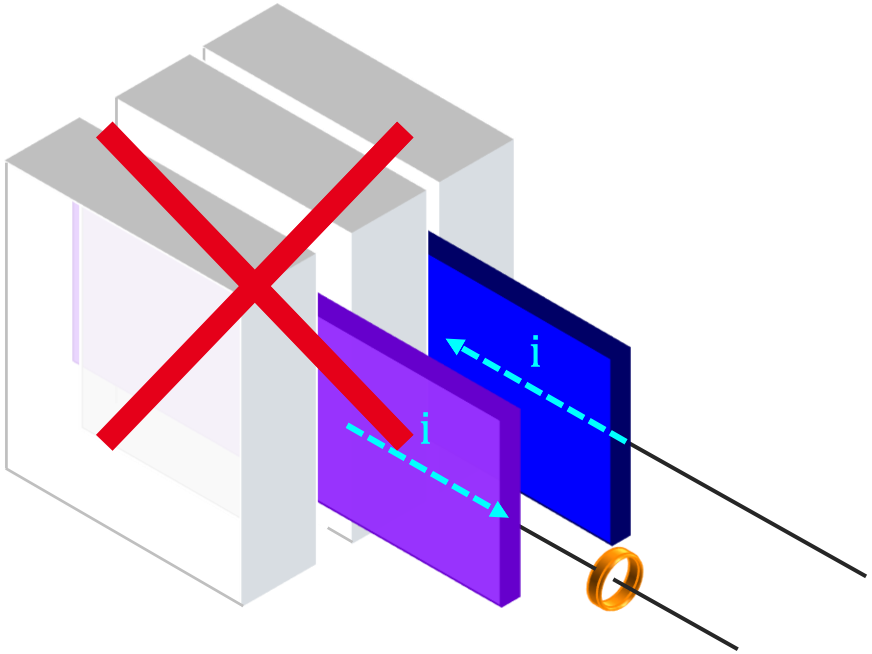

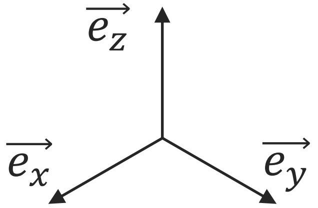

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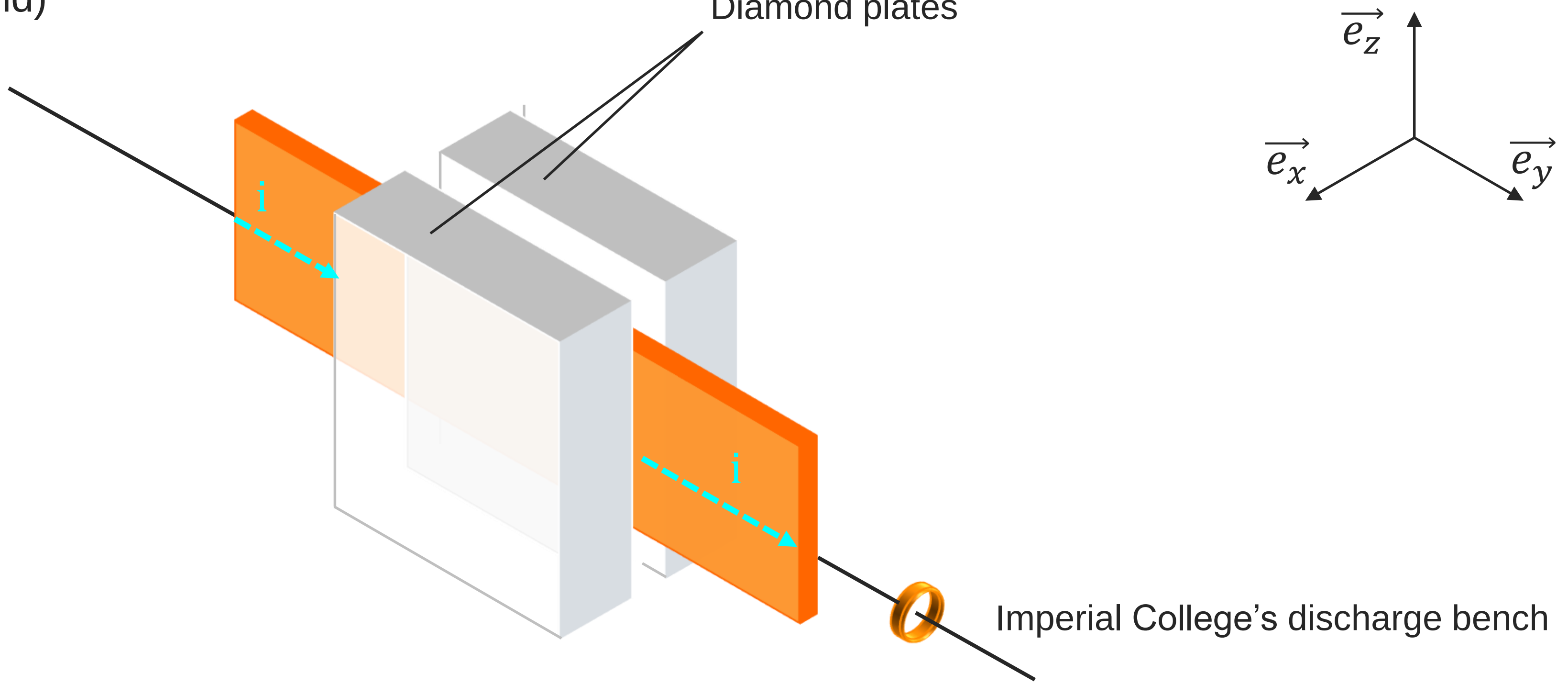

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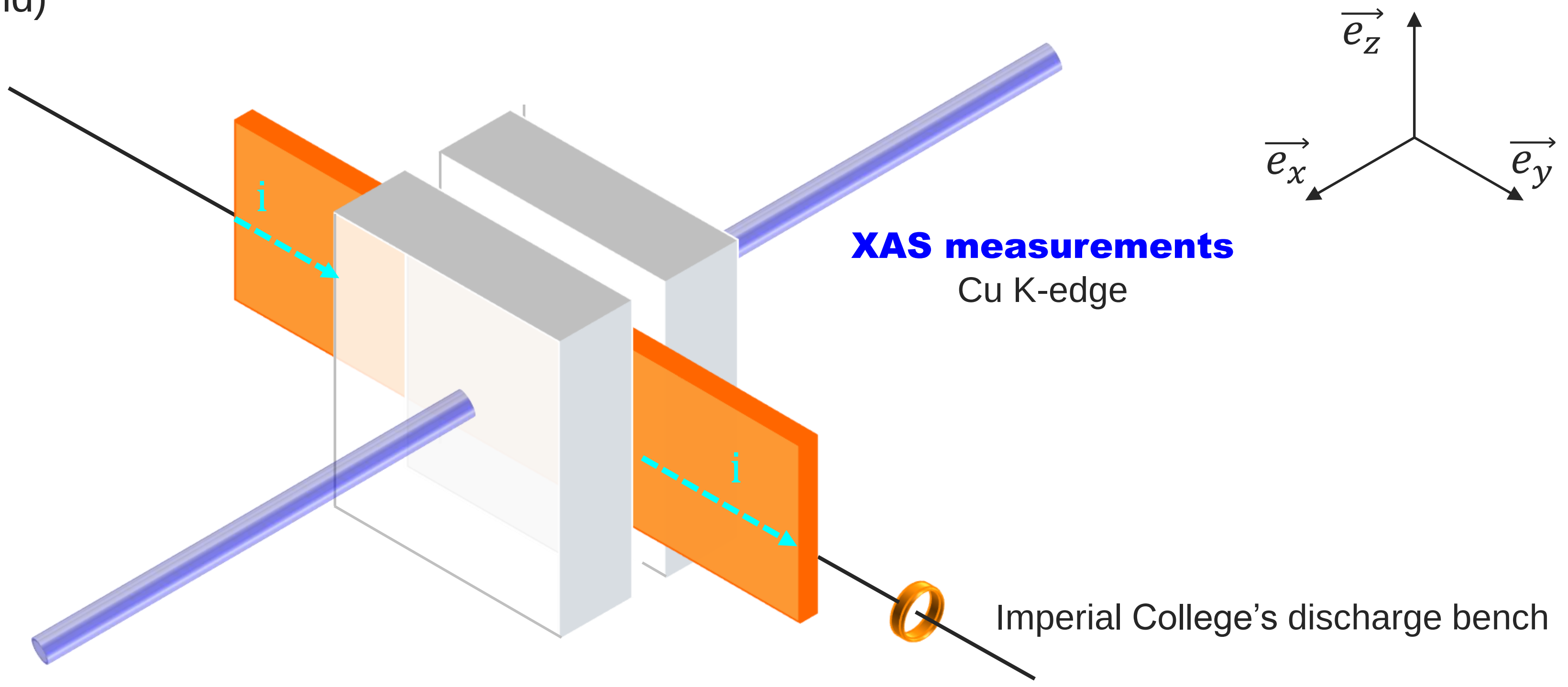

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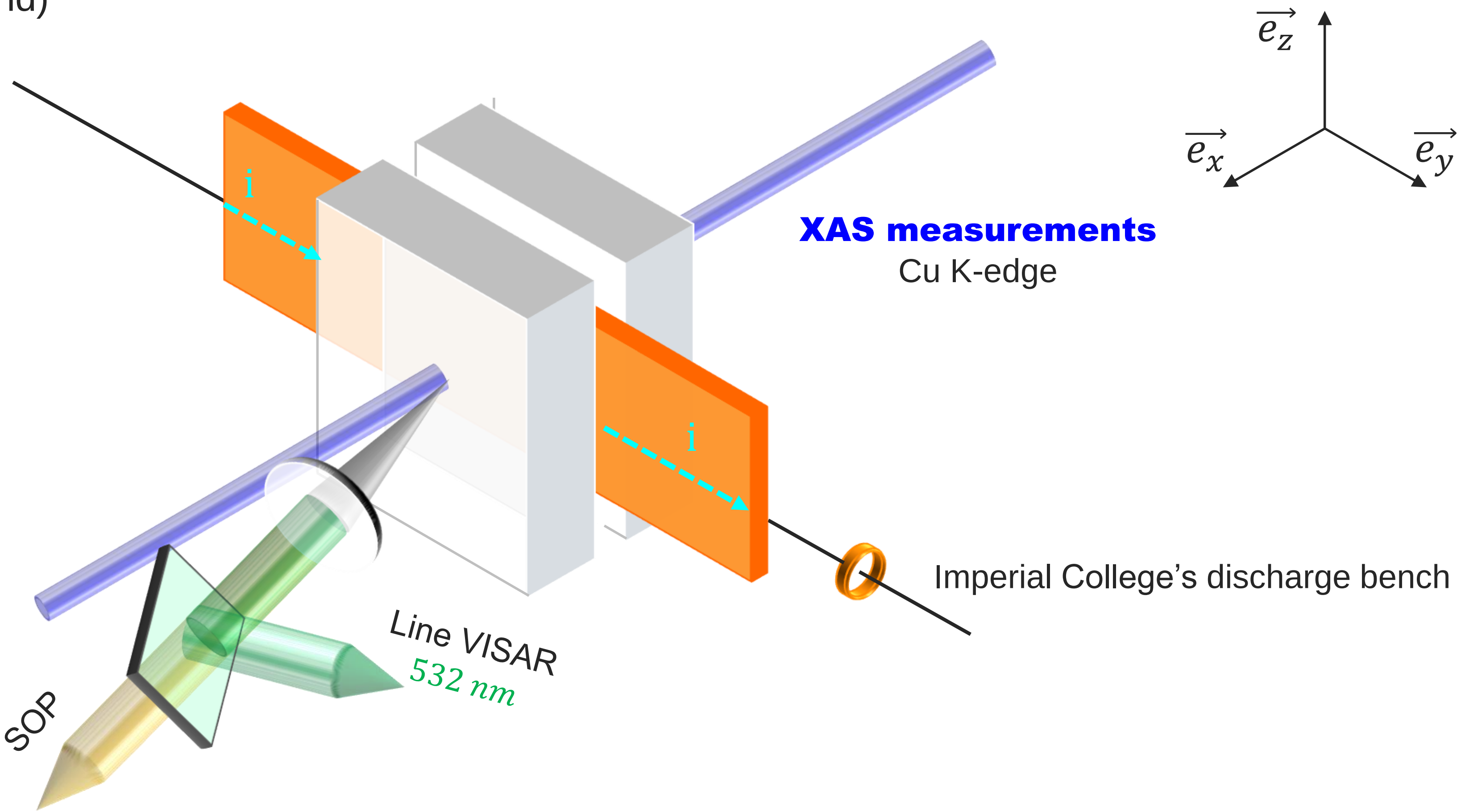

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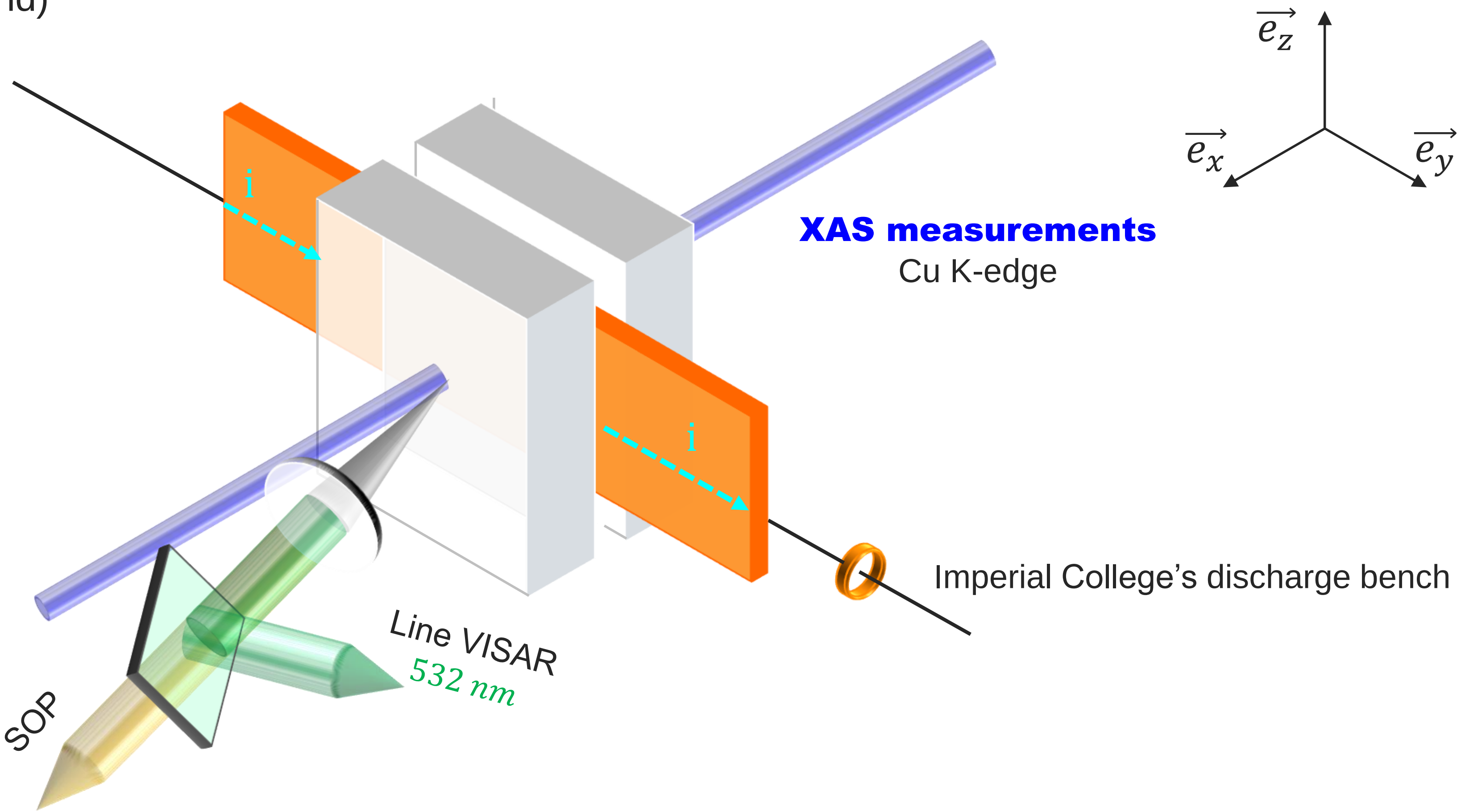
Measurements

- $U, I \rightarrow E_i$
- $U_p \rightarrow P, \rho, \sigma_e$
- $SOP \rightarrow T$
- $XANES \rightarrow T$

(through ab initio simulations)



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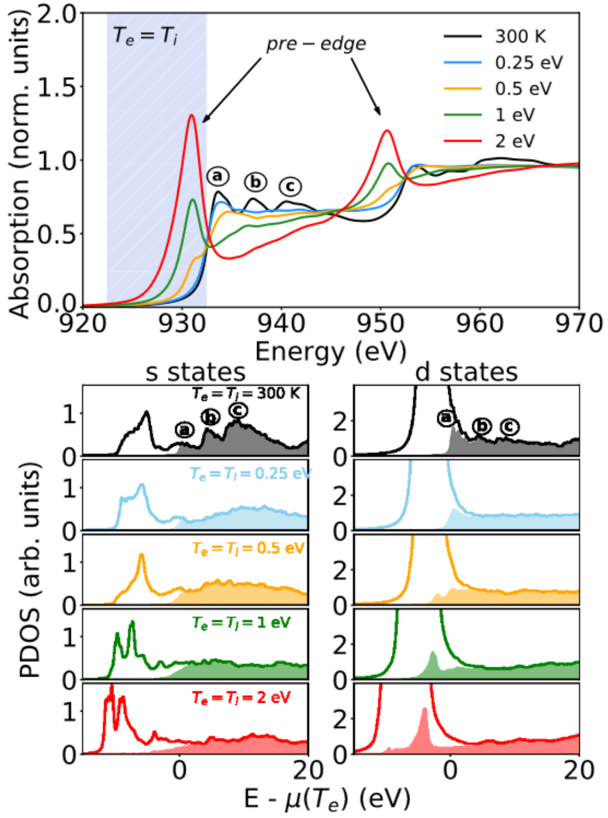
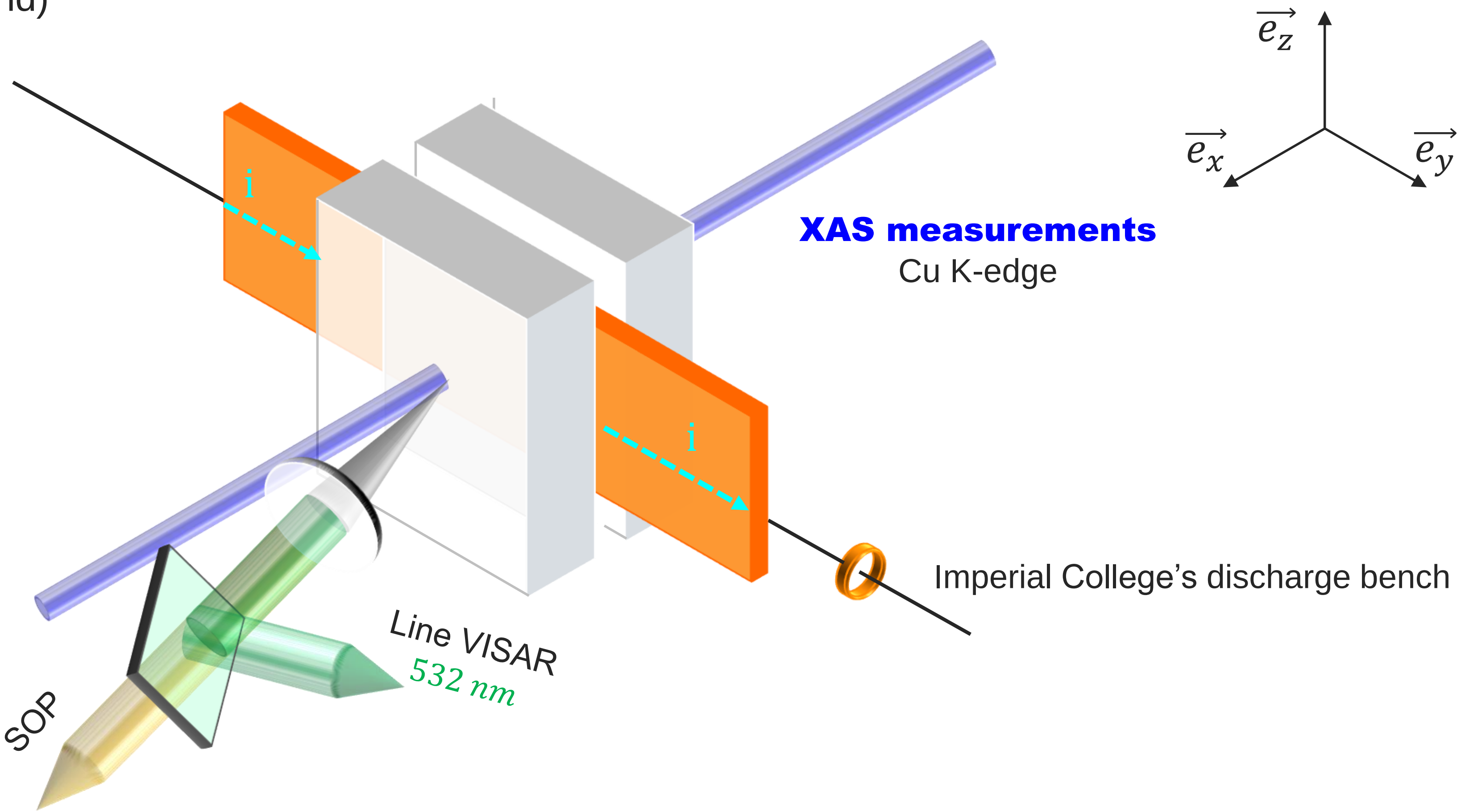
Imperial College London





[17] N. Jourdain et al, PRB, **101** 125127 (2020).

Thank you

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