US-Japan Workshop on Heavy Ion Fusion and High Energy Density Physics at Utsunomiya University

Semi-empirical Studies of Warm-Dense-Matter Physics using Fast Pulse Power Device

Toru Sasaki, Yuuri Yano, Mitsuo Nakajima, Tohru Kawamura,
and Kazuhiko Horioka
Department of Energy Sciences
Tokyo Institute of Technology

contact us: sasaki@es.titech.ac.jp

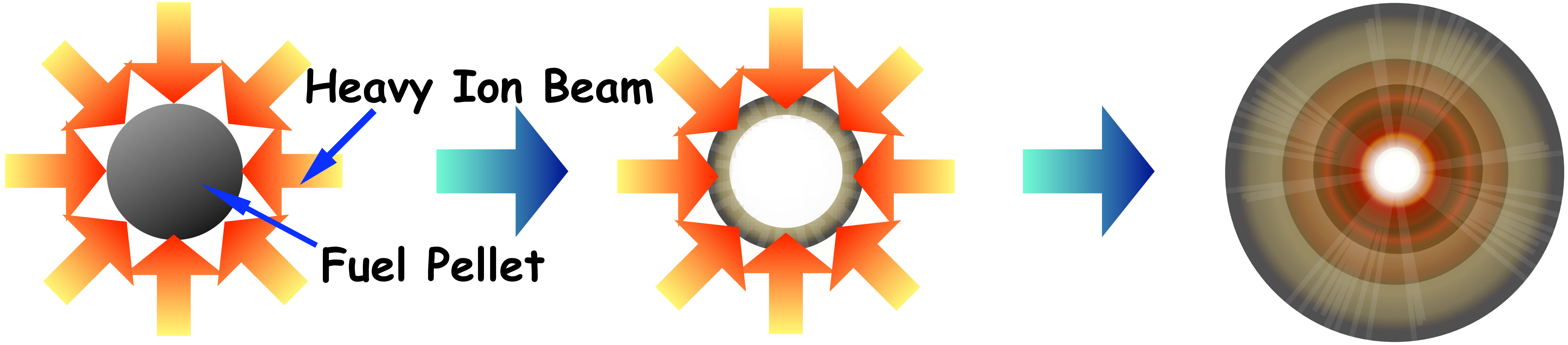
Background

HIF(Heavy Ion Fusion) Scenario

--- Heavy Ion Beams have to irradiate the pellet surface and uniformly deposit the drive energy.

Fluctuation of deposition energy and/or pressure should be less than a few % for ignition and high gain.

Estimate and Measure Warm Dense State
(ex. EOS, Transport Coefficient, Stopping Power)



Beam Irradiation Implosion Phase Ignition Phase

HIF Concept(Direct Irradiation)

Warm Dense State

Features of Warm Dense State

- ➢ **High Density and Low Temperature**
- ➢ **Debye Length < Ion Sphere Radius**

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{n e^2}} \qquad a = \left(\frac{3}{4\pi n}\right)^{1/3}$$

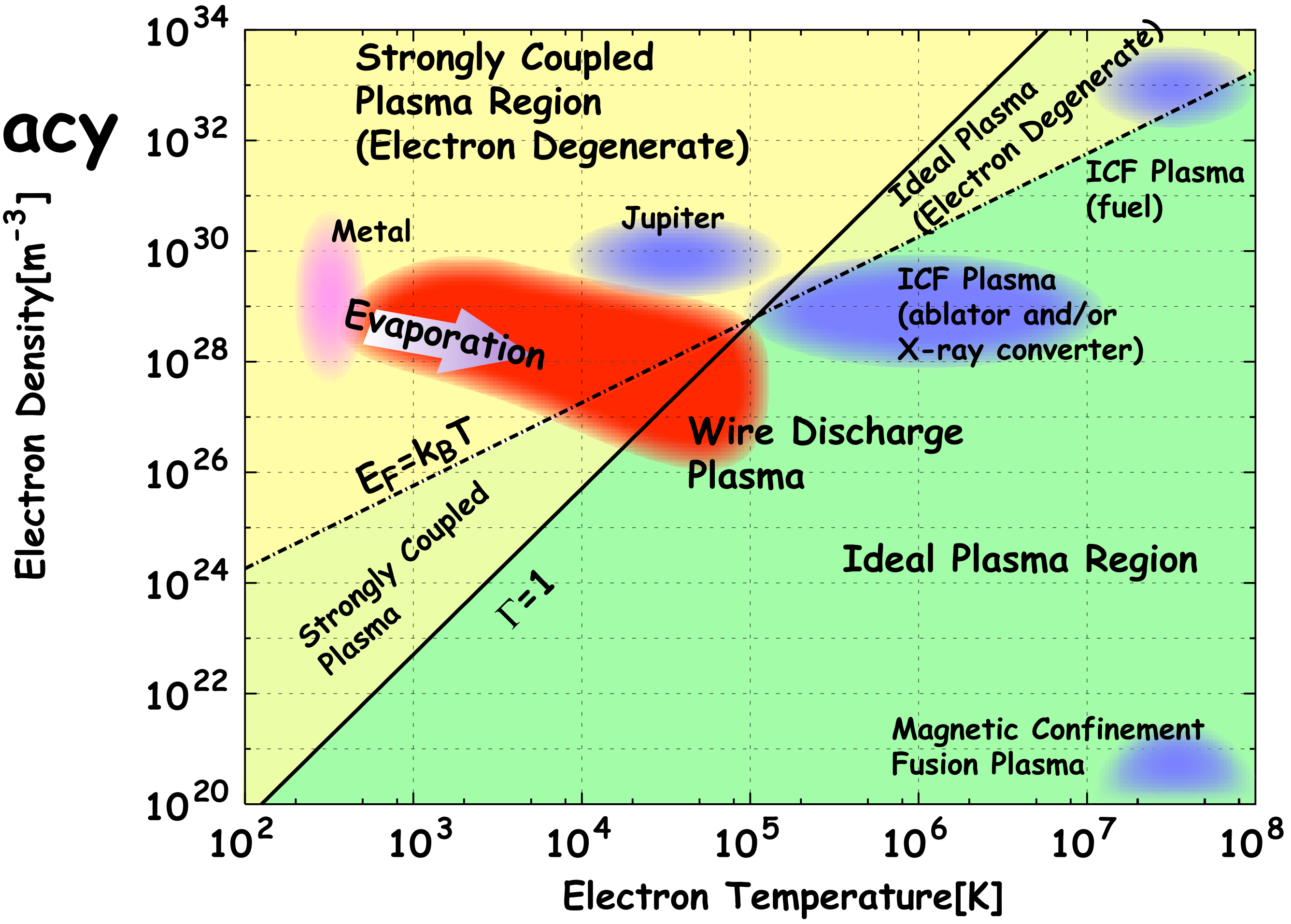
- ➢ **Electrons in High Degeneracy**

$$\theta = \frac{E_{kin}}{E_F} = \frac{k_B T}{\frac{\hbar^2}{2m_e}\left(3\pi^2 n\right)^{2/3}}$$

- ➢ **Coupled Plasma State**

--- $\Gamma > 1$

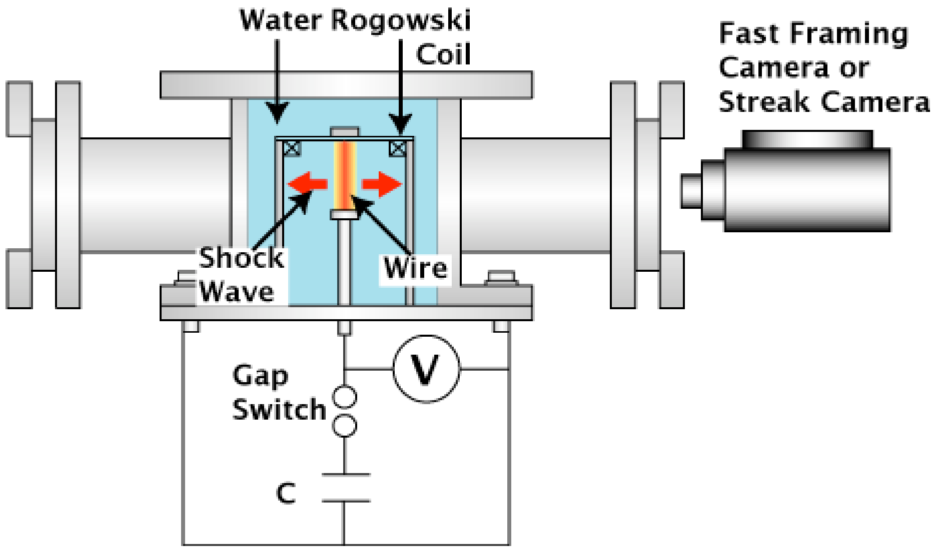
$$\Gamma = \frac{E_{pot}}{E_{kin}} = \frac{\frac{(Z^* e)^2}{4\pi\epsilon_0 a}}{k_B T}$$



Density-Temperature Diagram

Advantages of the Discharge Produced Plasma

Wire Discharges in Water



- Ease of Generation.
- Axial Symmetry.
- Ease of Evaluation of Conductivity and Input Energy History by Voltage and Current.
- Tamper Effect.
- Transparent.

Can compare the hydrodynamic behavior with 1-D Magneto Hydrodynamic(MHD) simulation.

Remark of This Study

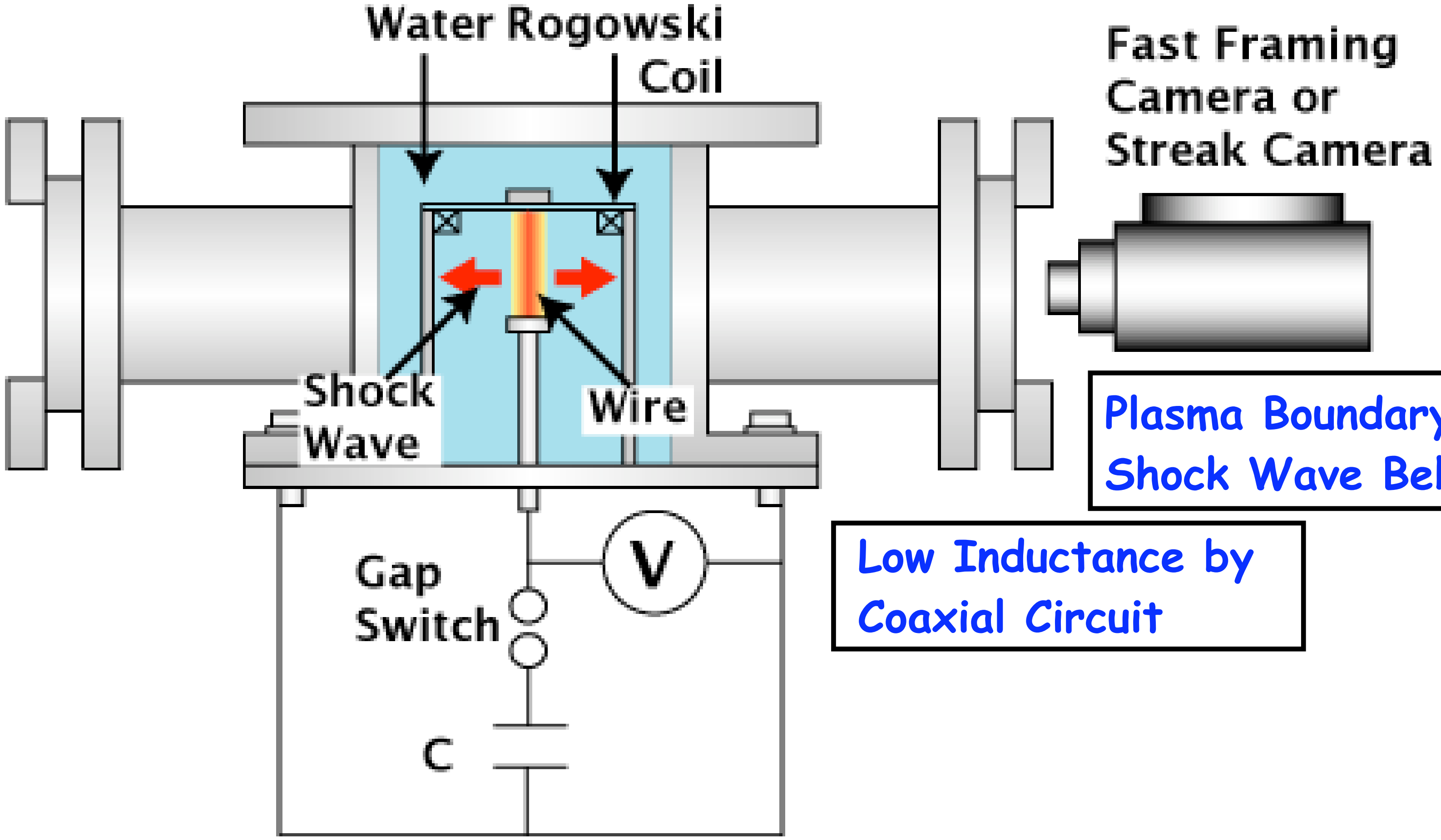
Fit the numerical shock and contact surface trajectories to the experimental ones.

Evaluate the Equation of State(EOS) models and transport coefficients using “Semi-empirical” fitting of hydrodynamic behavior.

- Evaluate EOS and transport coefficients in broad density-temperature range.

Experimental Setup

Experimental Set-up

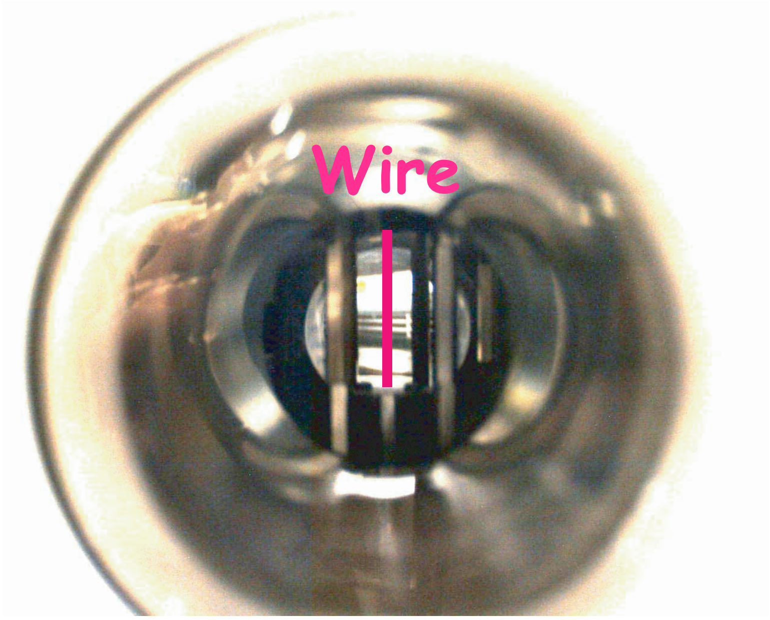


Experimental Arrangement

Load Section Filled with Water
- ➢ Tamper Effect
- ➢ Transparent

Plasma Boundary
Shock Wave Behavior

Low Inductance by
Coaxial Circuit

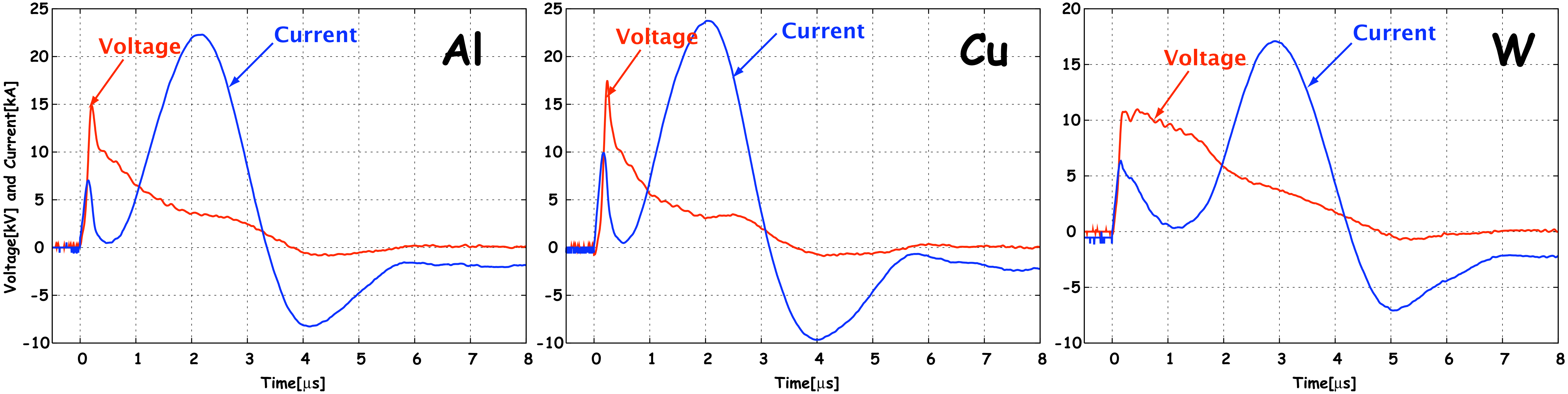


Picture of Load Section

Charge Voltage: 10kV
C: 3.2μF
Circuit Inductance: 103nH
Load: Al, Cu and W Wire (ψ=100um)

Typical Waveforms

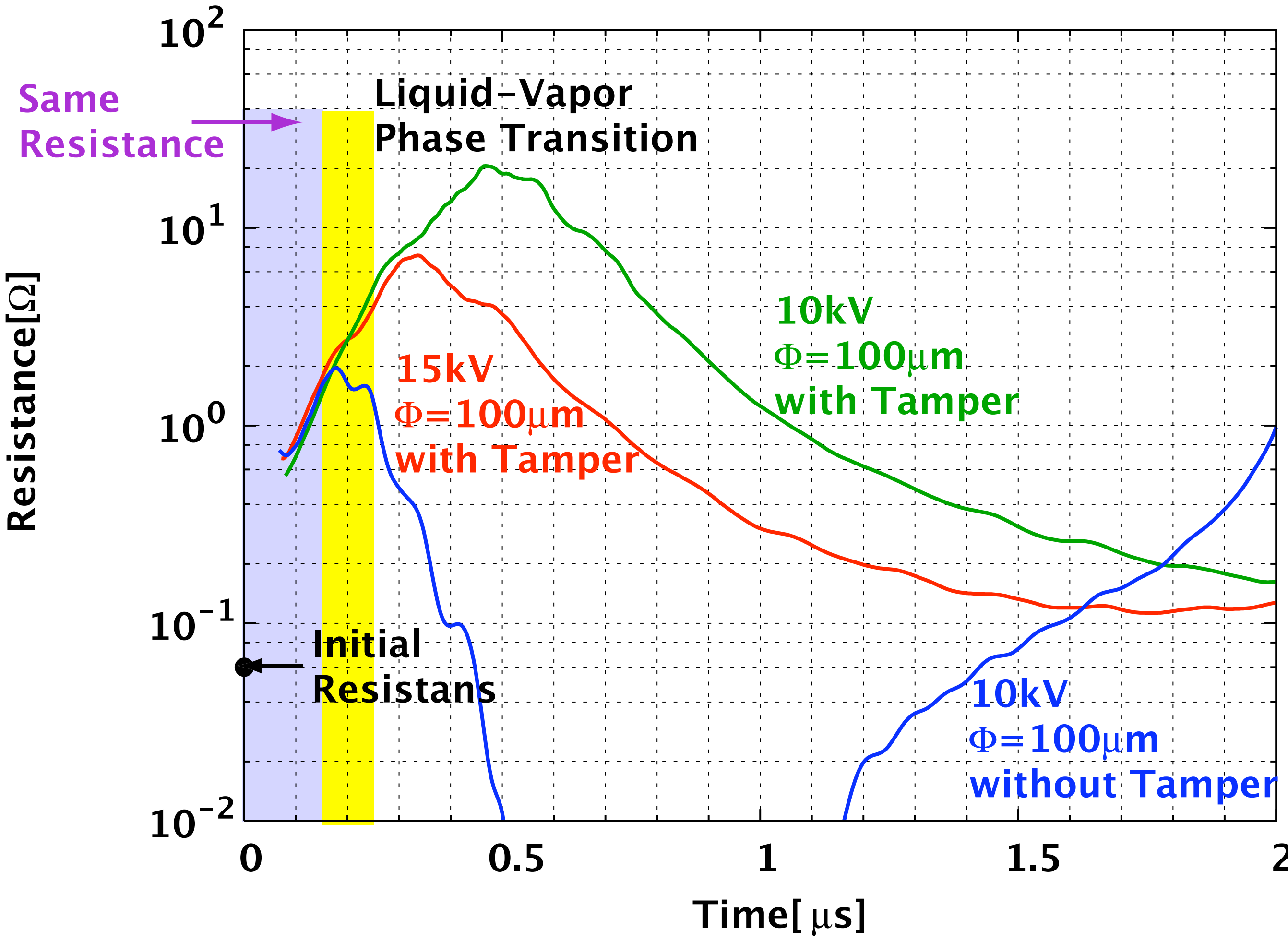
Typical Waveforms for Wire Discharges

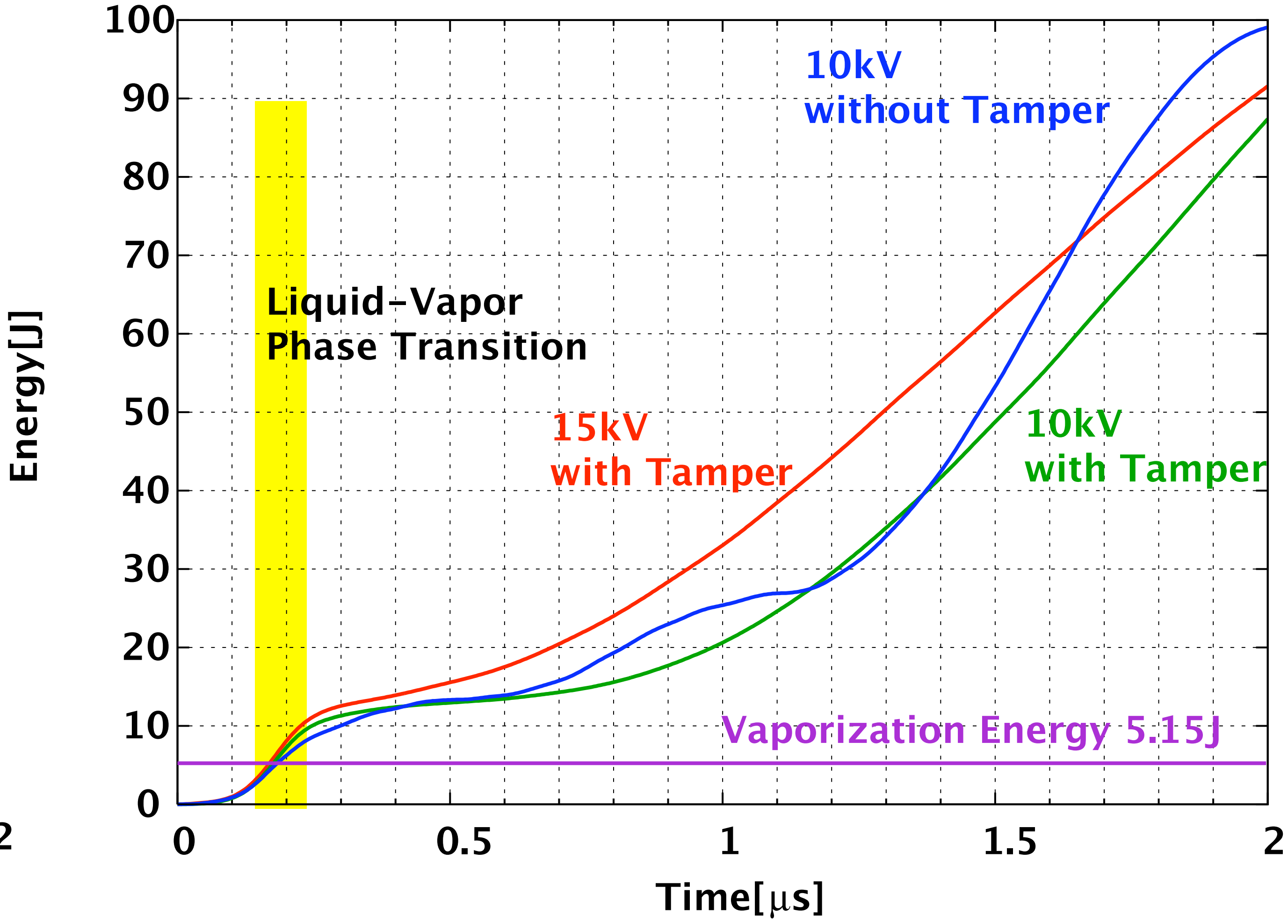


- ➢ The current waveform has sharp peak at starting phase.
- ➢ The voltage waveform depends on the wire materials.
- ➢ Waveforms are reproducible.

Definition of Evaporation Timing

Comparison of Resistance and Input Energy History for Al-Wire





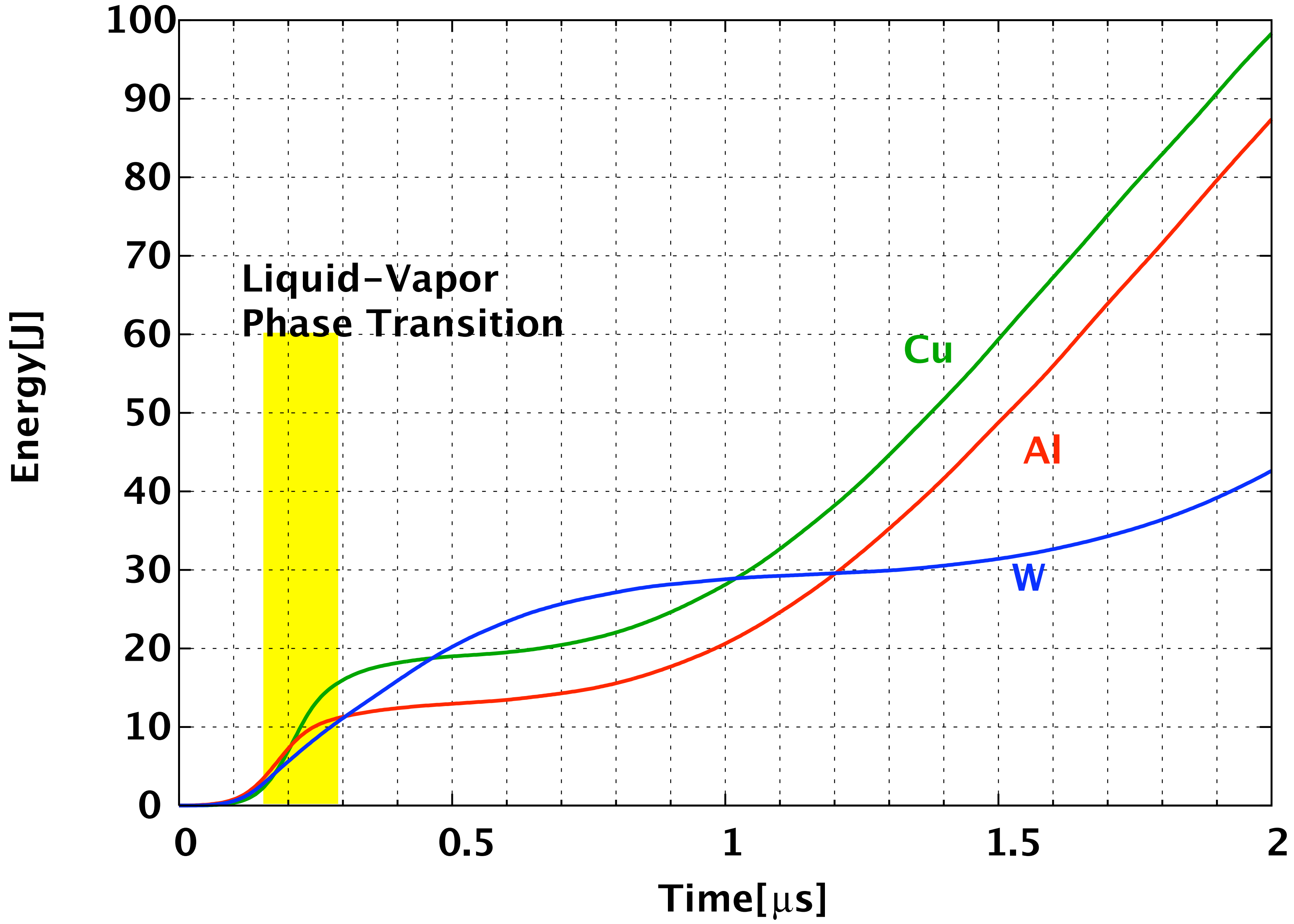
➢ The evolutions of resistance didn't depend on the discharge condition until 200ns.

➢ The input energy exceeded the vaporization energy at 200ns.

(With Tamper means in Water, Without Tamper means in Air.)

Evolution of Input Energy

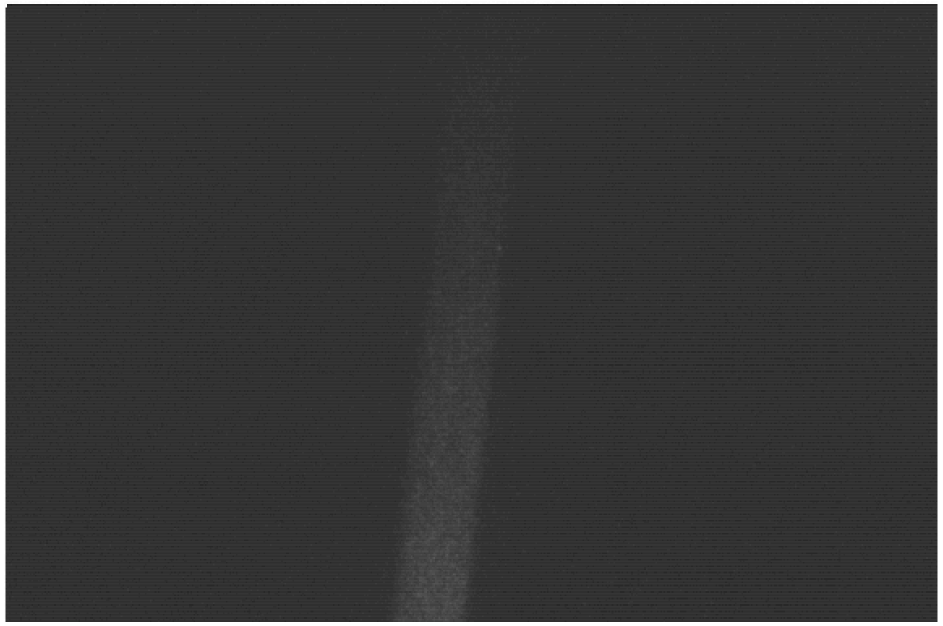
Comparison of Input Energy History



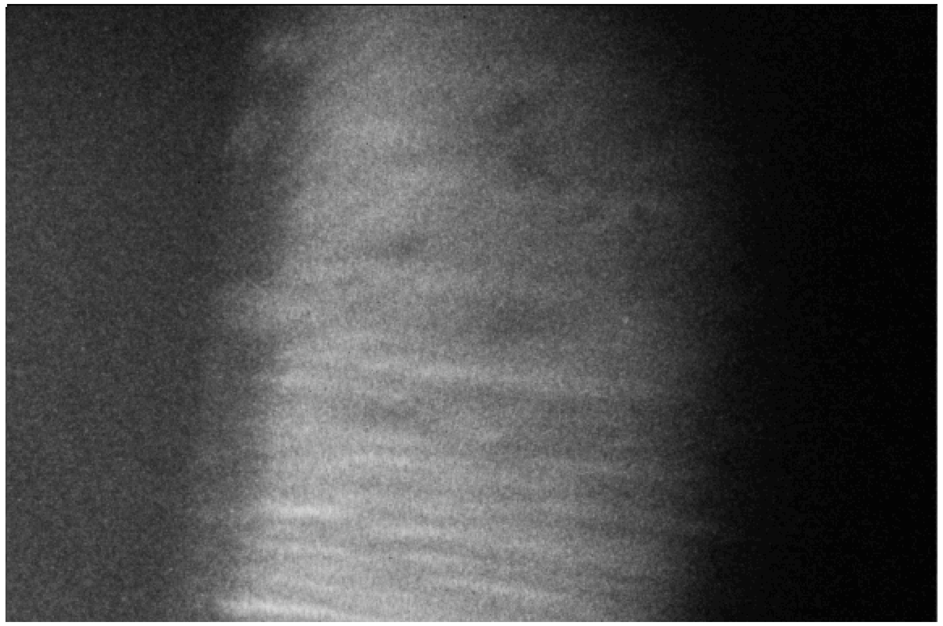
▶ Evolution of energy was dependent on initial resistance.

Evolution of Plasma Boundary

Framing Photographs and Evolution of Plasma Boundary

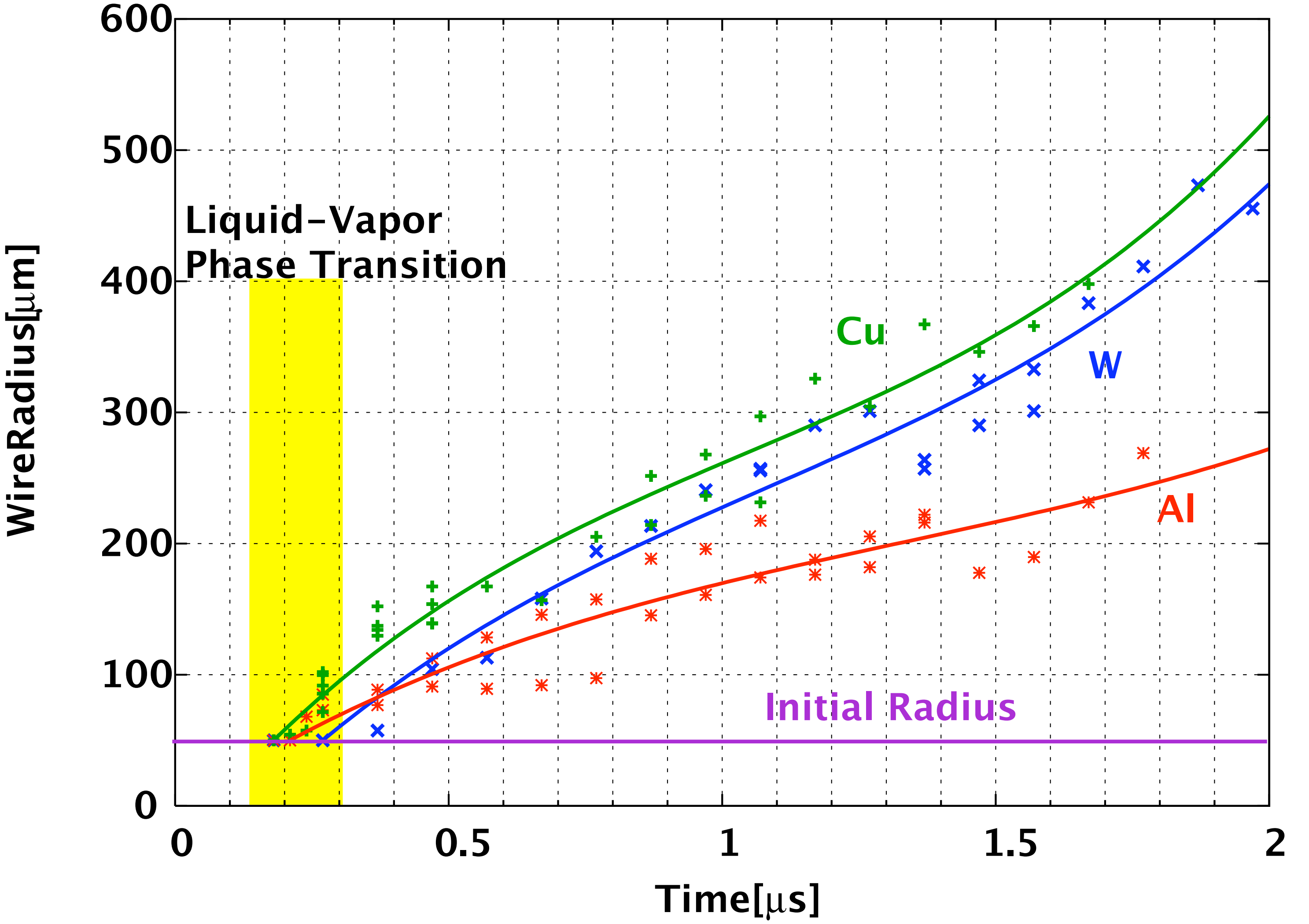


(a) 180-190ns



(b) 1070-1080ns

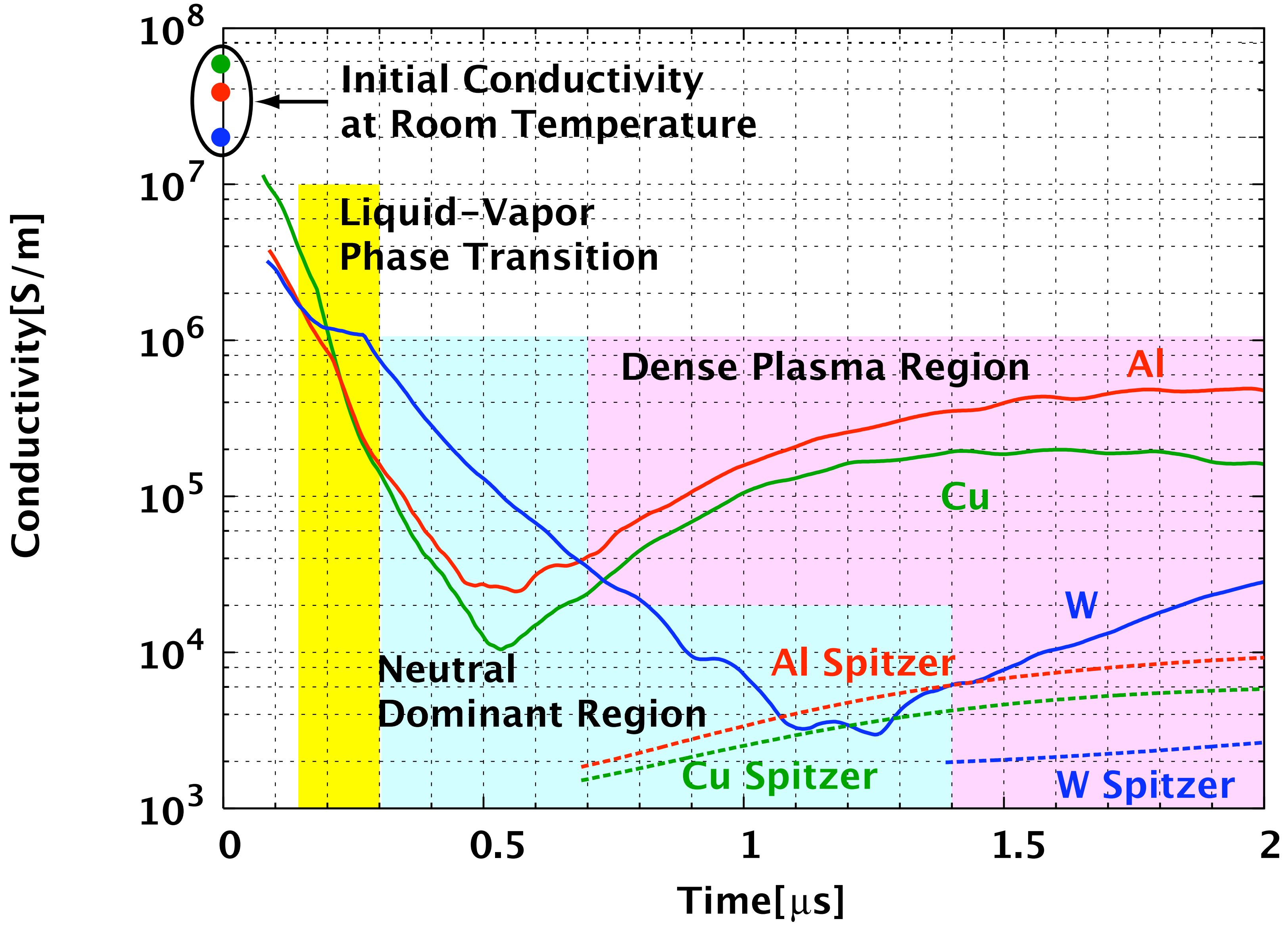
Framing Photos (Al:φ=100μm)



Plasma Radius History

▶ Evolution of plasma radius depended on Evolution of Input Energy.

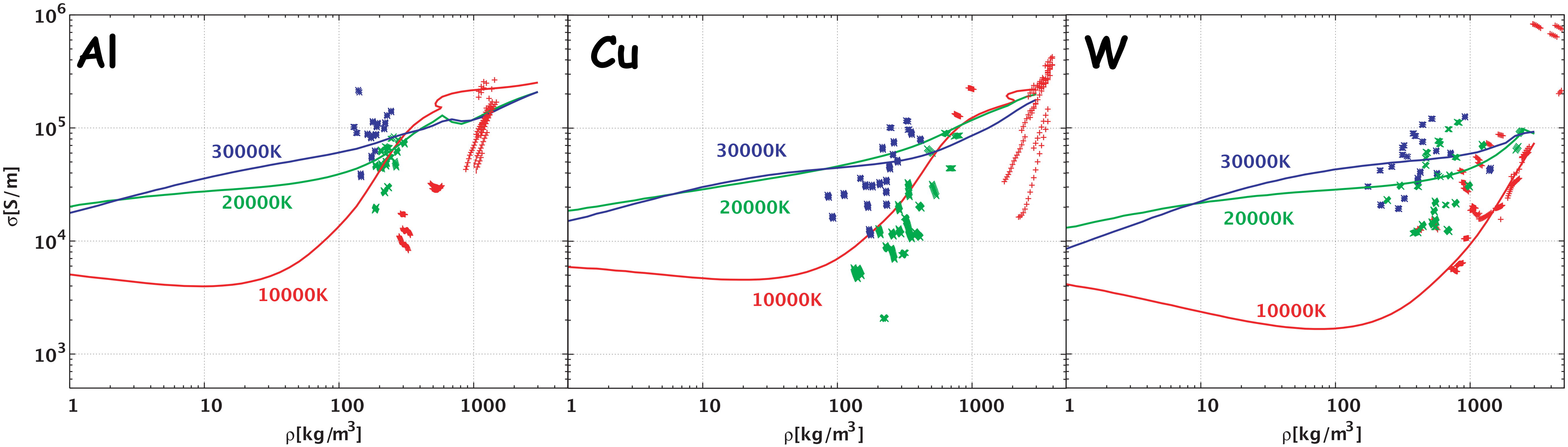
Evolutions of Conductivity



- ➢ Conductivity curve has a bottom at ~500ns for Al and Cu-Wire, at ~1.2us for W-Wire.
- ➢ About 10 times compared with Spitzer's conductivity.

Evaluation of Conductivity

Evaluations of Conductivity for Each Wires.



➢ The theoretical model[1] coincides with our results at high temperature.

➢ The low temperature(10000K) region can't be explained by the conventional model.

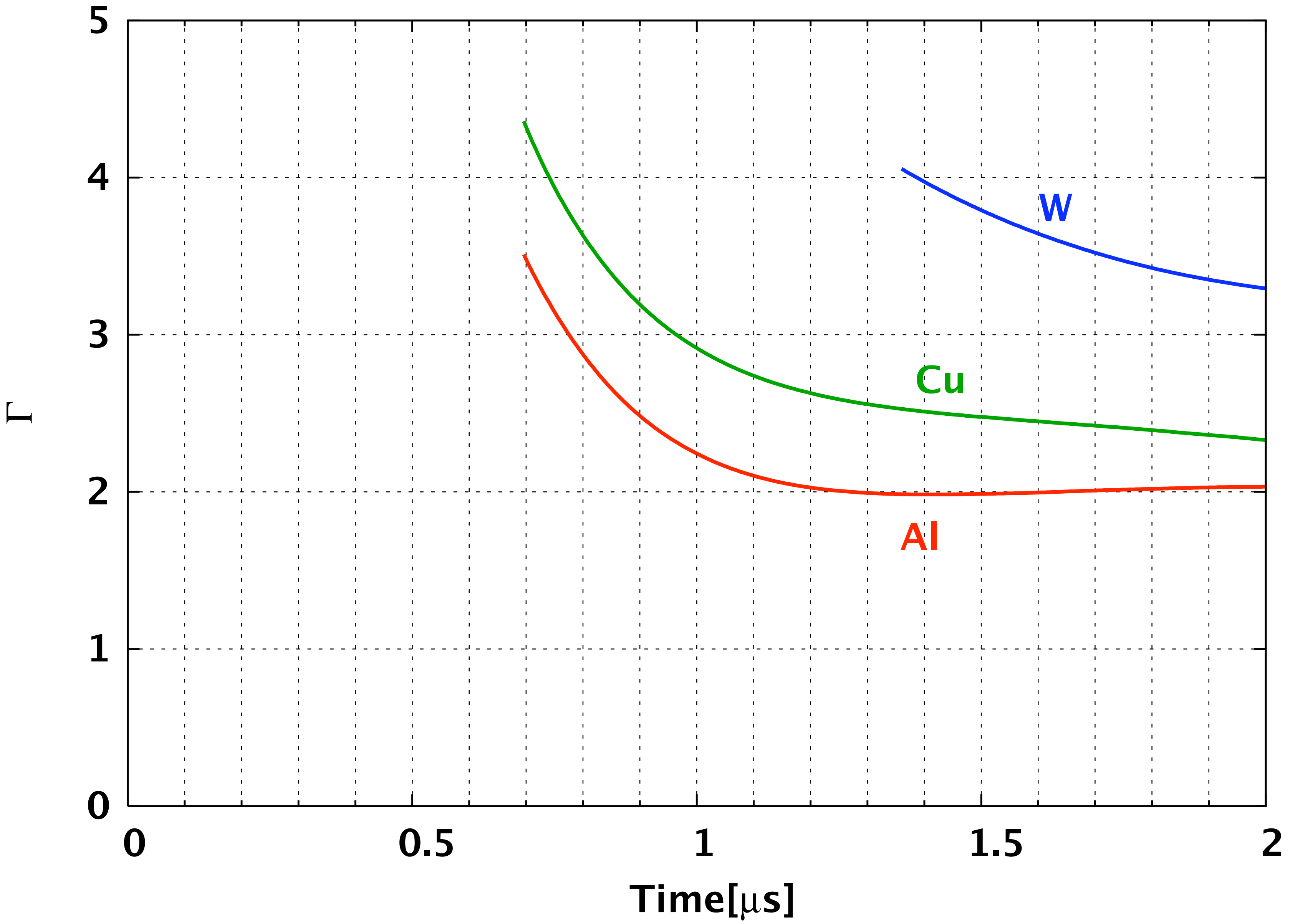
➢ Wide parameter region is covered using pulse-power discharges in water.

[1] S. Kuhlbrodt et. al., Contrib. Plasma Phys., 45, 73(2005)

Evolution of Coupling Parameter

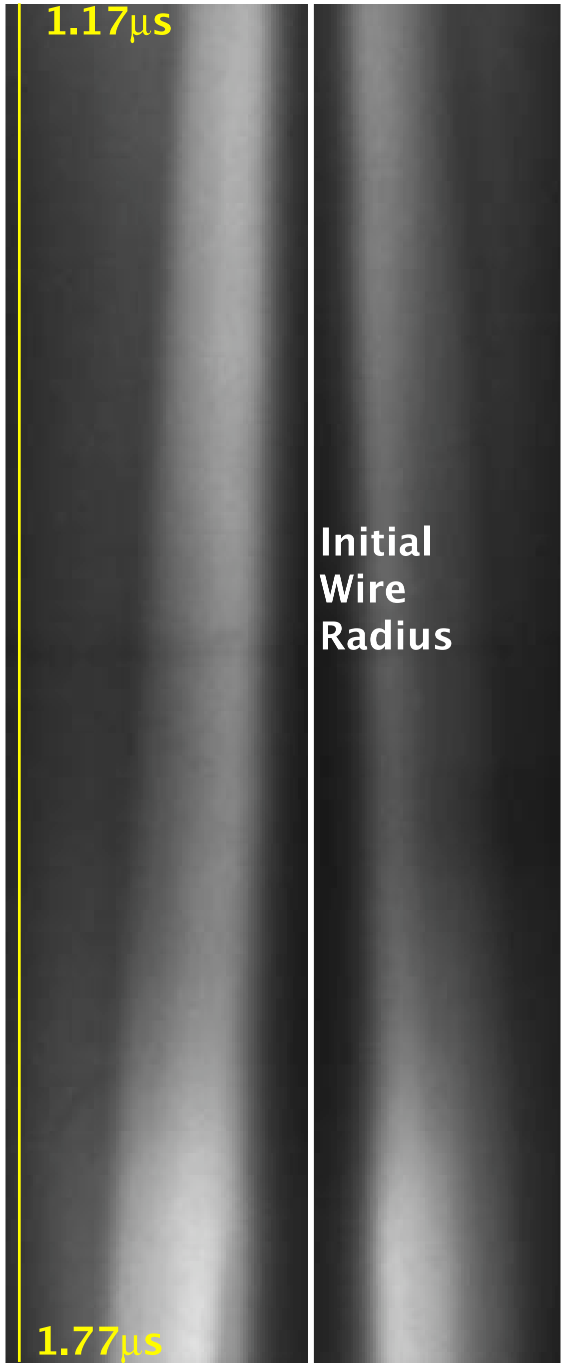
$$\Gamma = \frac{E_{pot}}{E_{kin}} = \frac{\frac{(Z^* e)^2}{4\pi\epsilon_0 a}}{k_B T}$$

Evolutions of Estimated Coupling Parameter

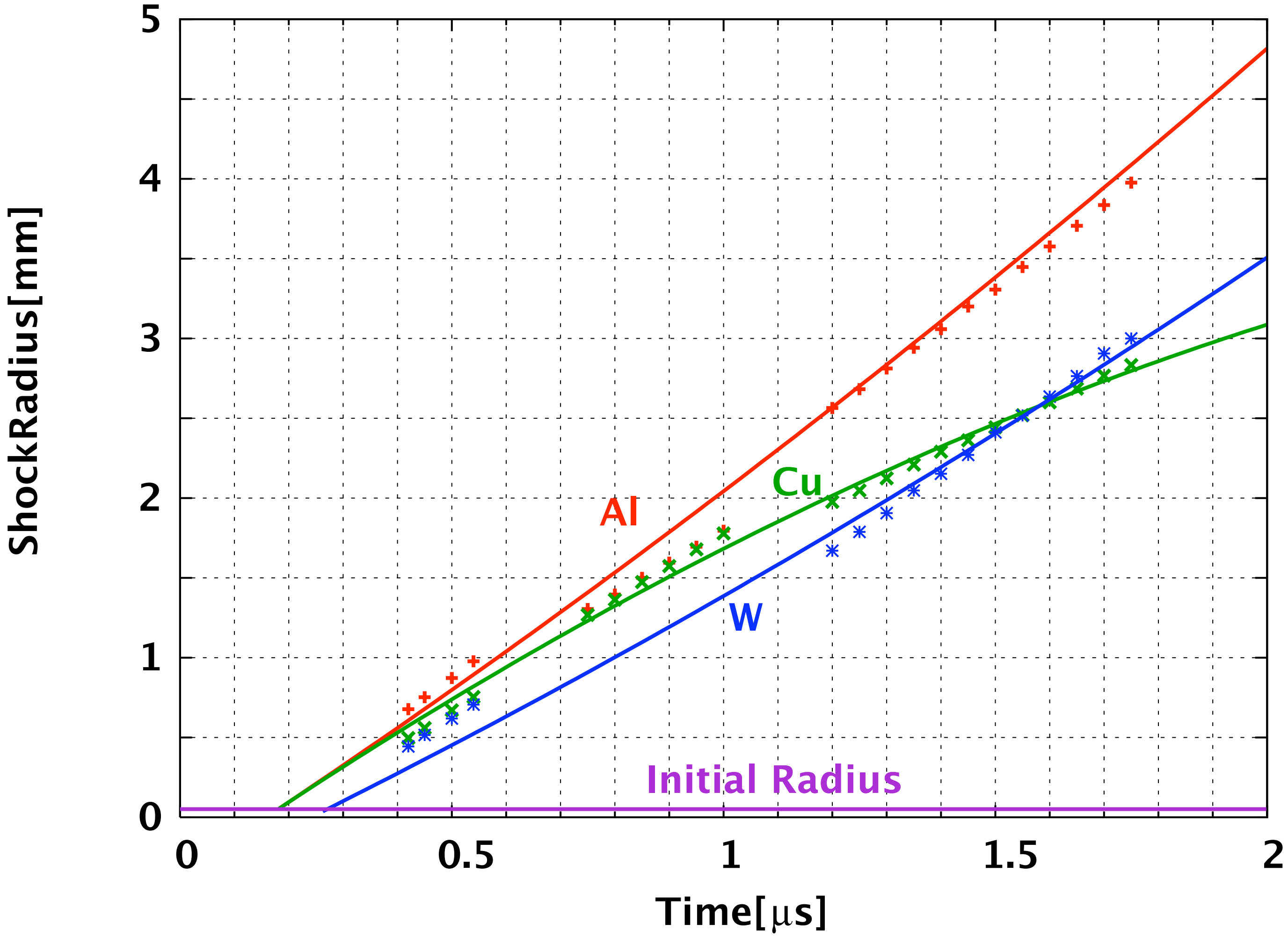


- ▶ Wire plasma maintains dense state up to 2μsec.
- ▶ Coupling parameter plateaus at Γ~2 for Al-Wire, Γ~2.5 for Cu-Wire and Γ~3 for W-Wire.

Evolution of Shock Wave



Shadow Graph Image of Cu-Wire Explosion

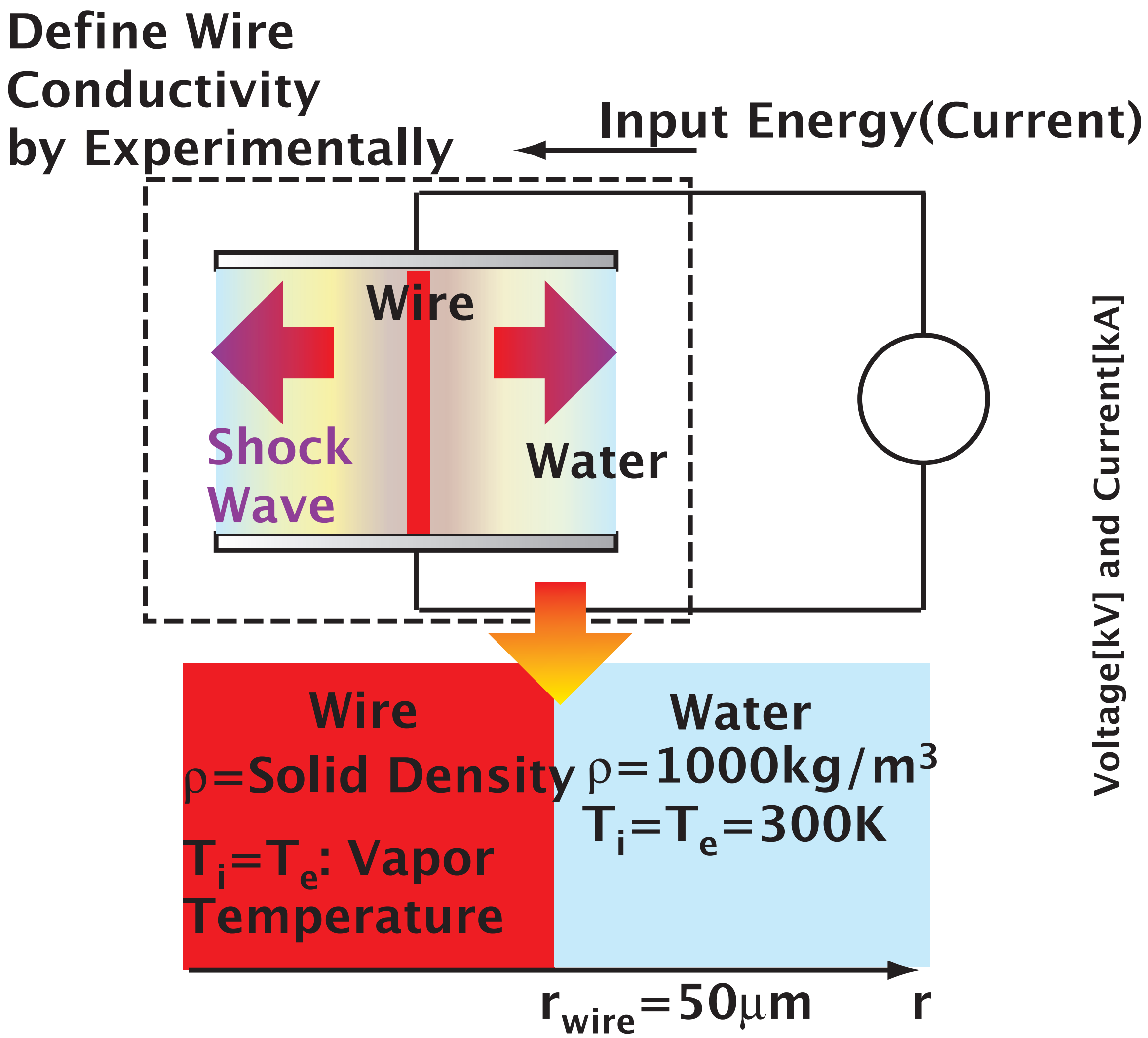


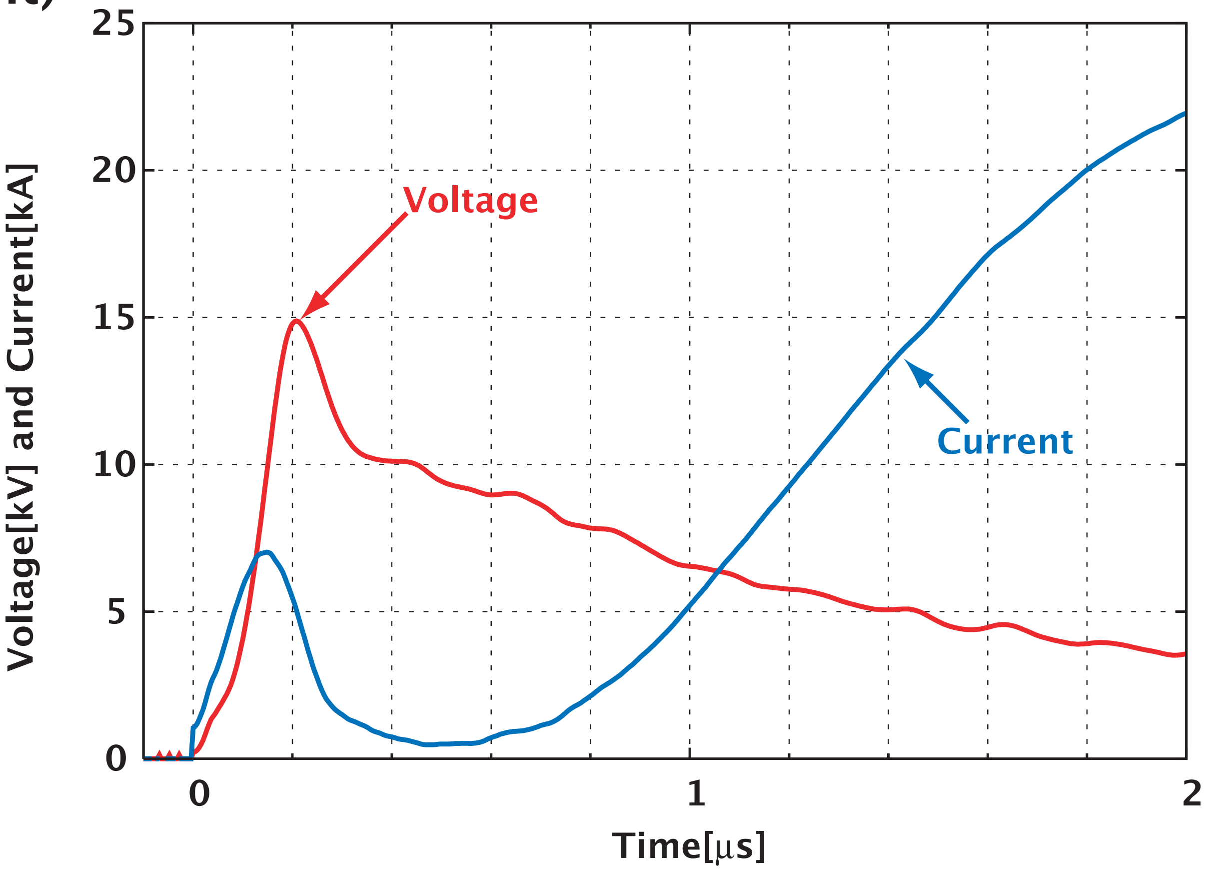
Shock Wave History in Water Induced by Wire Explosion

Evolution of shock wave in experimental results are $R(t) \neq t^{1/2}$

Initial Condition

Initial Condition





Setting of Equation of State(EOS)-> Water: IAPW95[2]

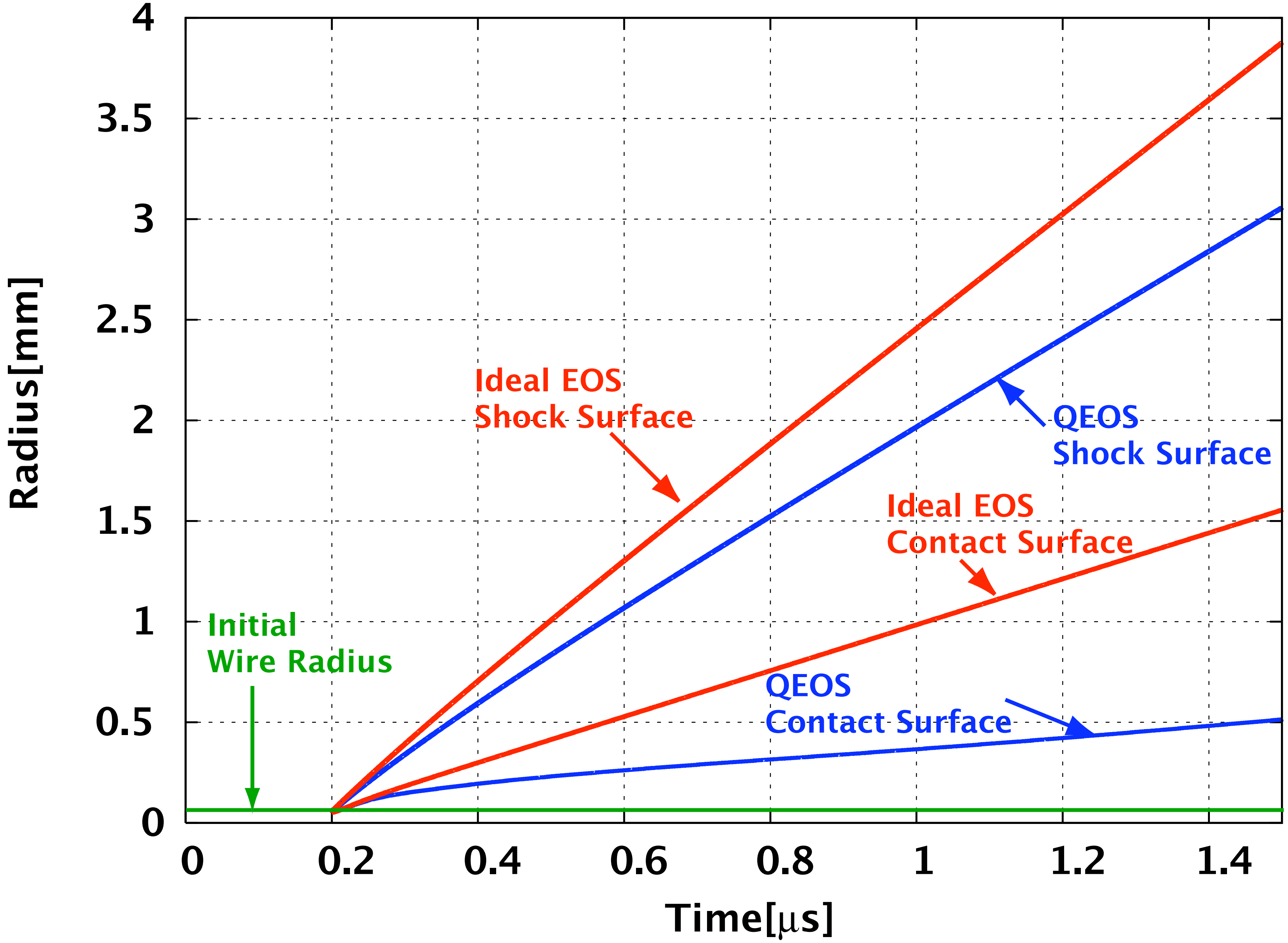
-> Wire: QEOS[3] or Ideal EOS

[2] IAPWS Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use, IAPWS Secretariat(1996).

[3] R. M. More, et. al., Phys. Fluids 31, 3059 (1988)

Comparison of Hydrodynamic Behaviors

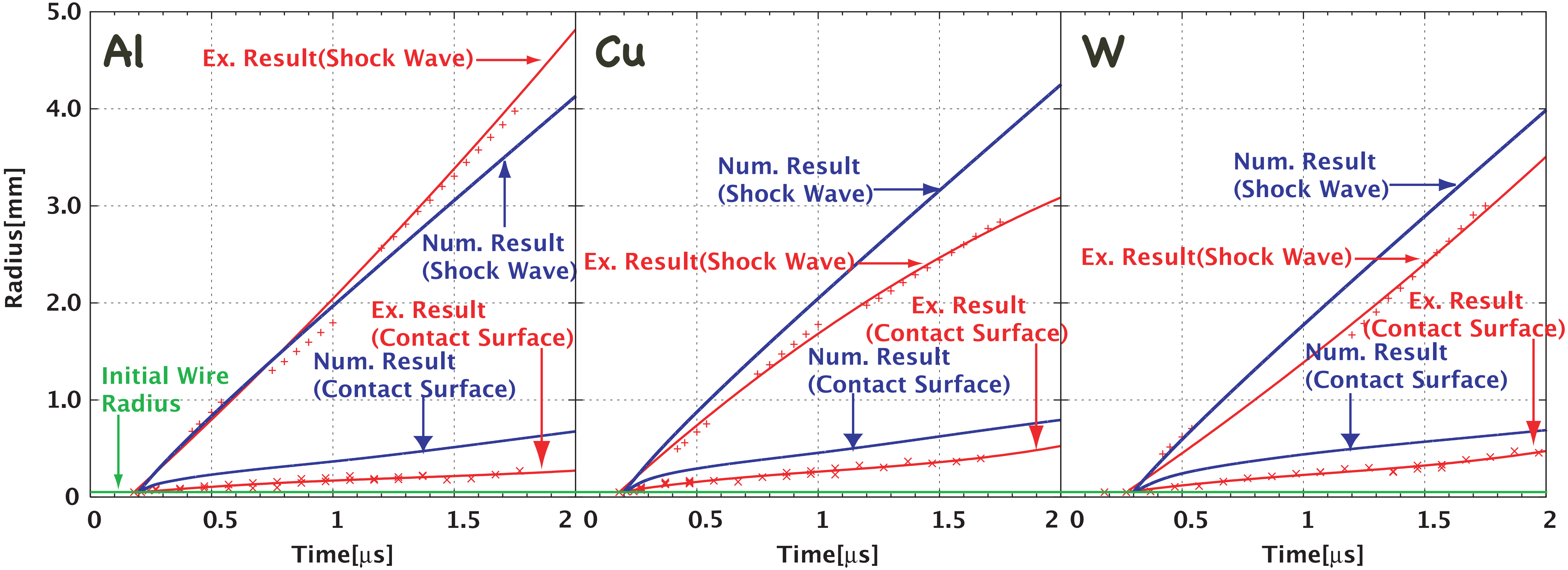
Effect of Equation of State



➢ The shock and contact surface trajectories are strongly depended on Equation of State(EOS).

Comparison with Experimental Observation

Comparison of the Numerical(QEOS) and Experimental Results



- ➢ Discrepancy of the hydrodynamics indicates the requirement of more accurate EOS model.

Summary

- The theoretical model for conductivity can explain the experimental results at high temperature region. However, results at low temperature region indicate the requirement of more accurate model for the prediction of the plasma temperature and EOS.

- Observed discrepancy of the numerical and the experimental behaviors of the hydrodynamics indicates the requirement of more accurate EOS at Warm Dense region.

- The 'semi-empirical' fitting of the contact surface and the shock wave evolution accompanied with the exploding wire discharges in water is proposed for the studies of plasma at Warm Dense State. Because, the hydrodynamic behaviors are strongly affected by the EOS models.