Opening Switches

Fall, 2018

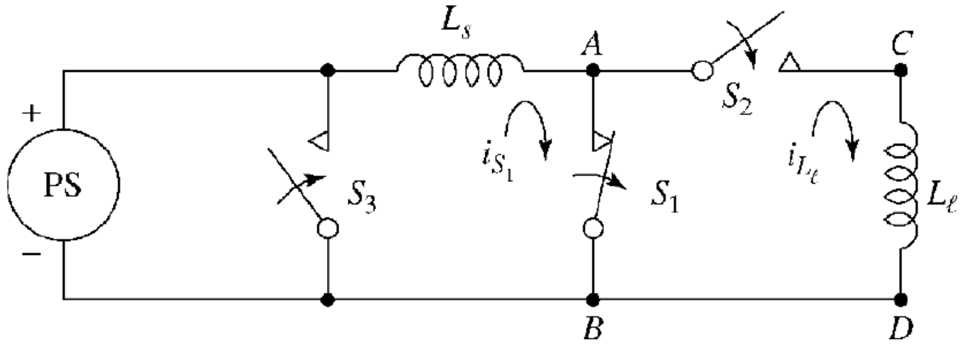
Kyoung-Jae Chung

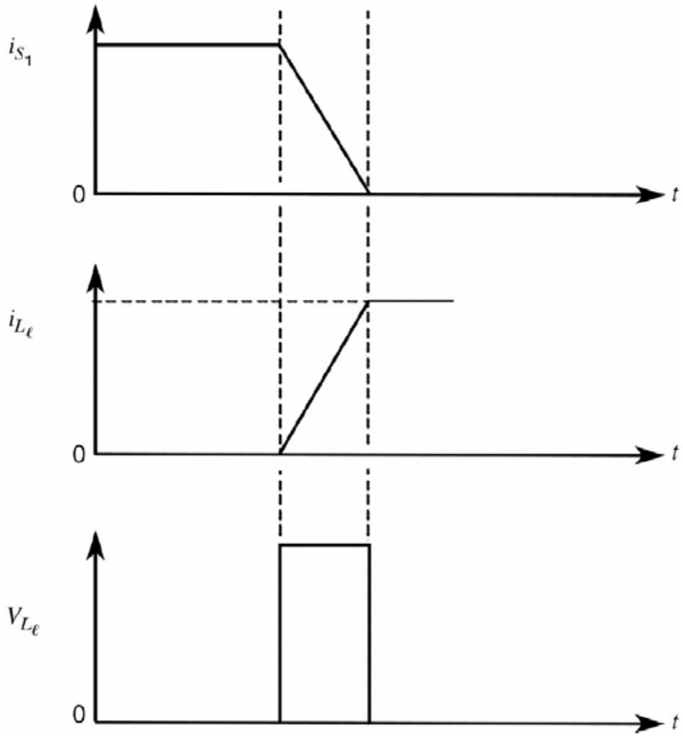
Department of Nuclear Engineering

Seoul National University

Introduction

- An opening switch is a device that conducts current in a low-impedance state until a command trigger turns it to a high-impedance state with no current conduction. It is a critical component for inductive storage systems.

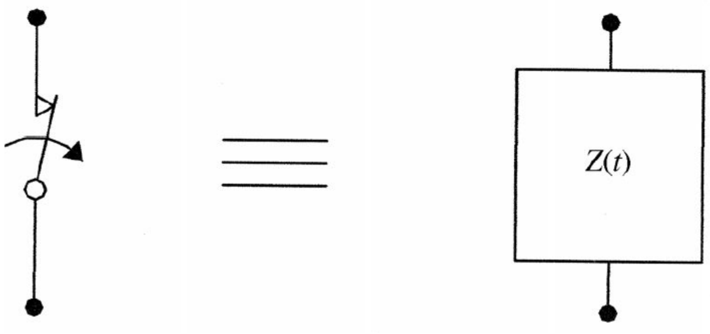


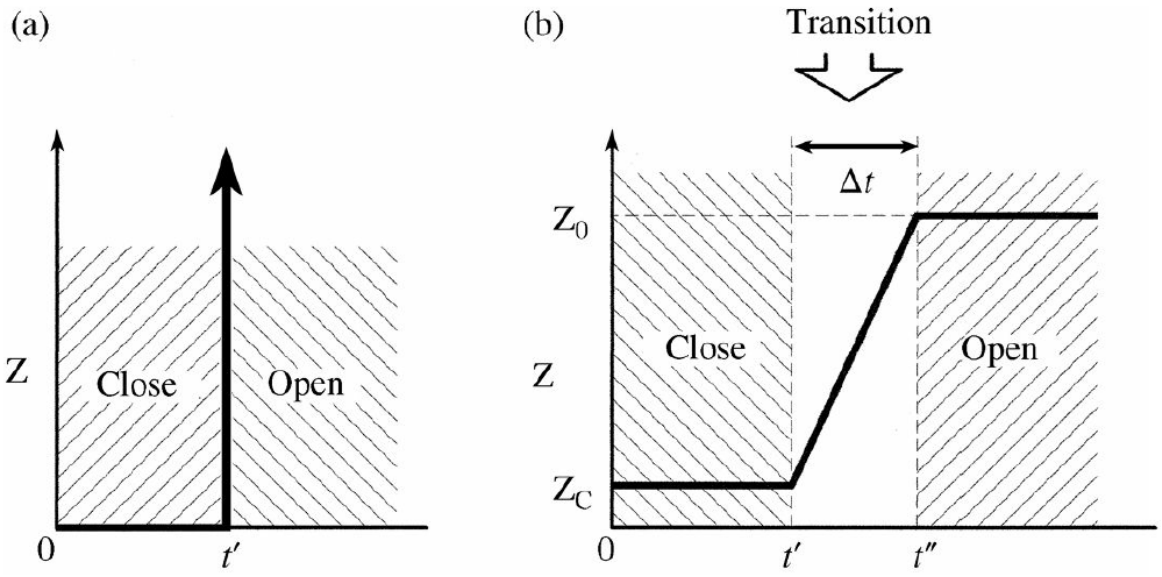


- Requirements for a good opening switch
  - Long current conduction time
  - Large current and small losses during conduction
  - Fast impedance rise
  - High impedance after opening
  - Large voltage hold-off during current interruption
  - Short recovery time for repetitive use
  - Long lifetime

Equivalent circuit

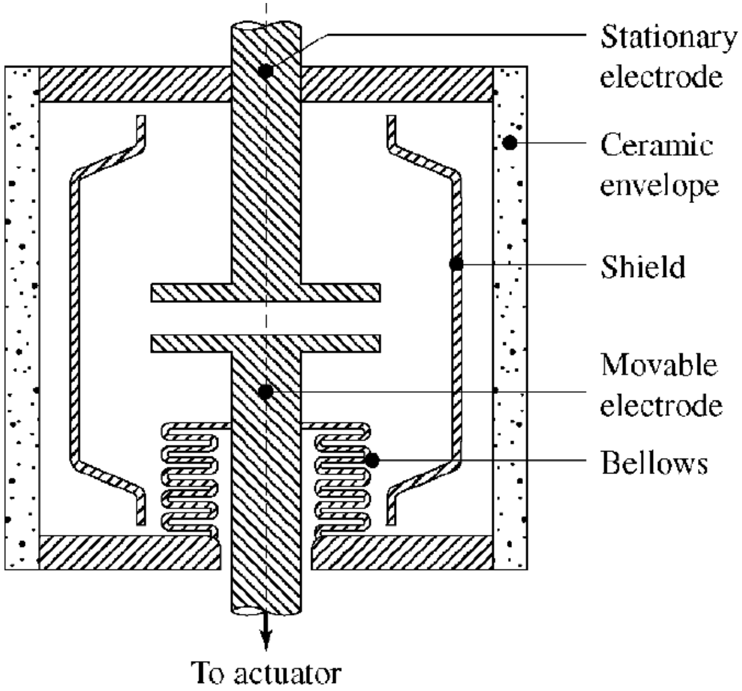
- The equivalent circuit of an opening switch is a time-varying impedance, wherein the impedance increases with time.





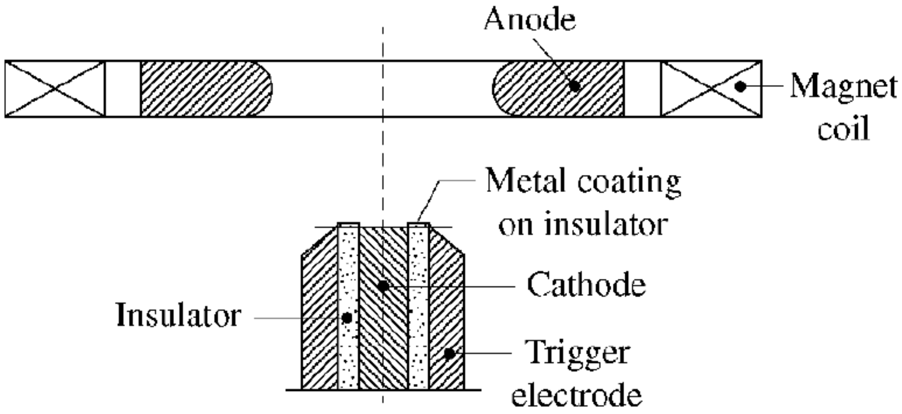
Vacuum circuit breaker

- The switch closure is done by mechanically bringing the two electrodes together to make physical contact. The opening is achieved by physically separating the two electrodes. The arcing, which ensues upon separation, continues until the natural current zero (in the case of AC schemes) is achieved, which leads to the arc extinction.



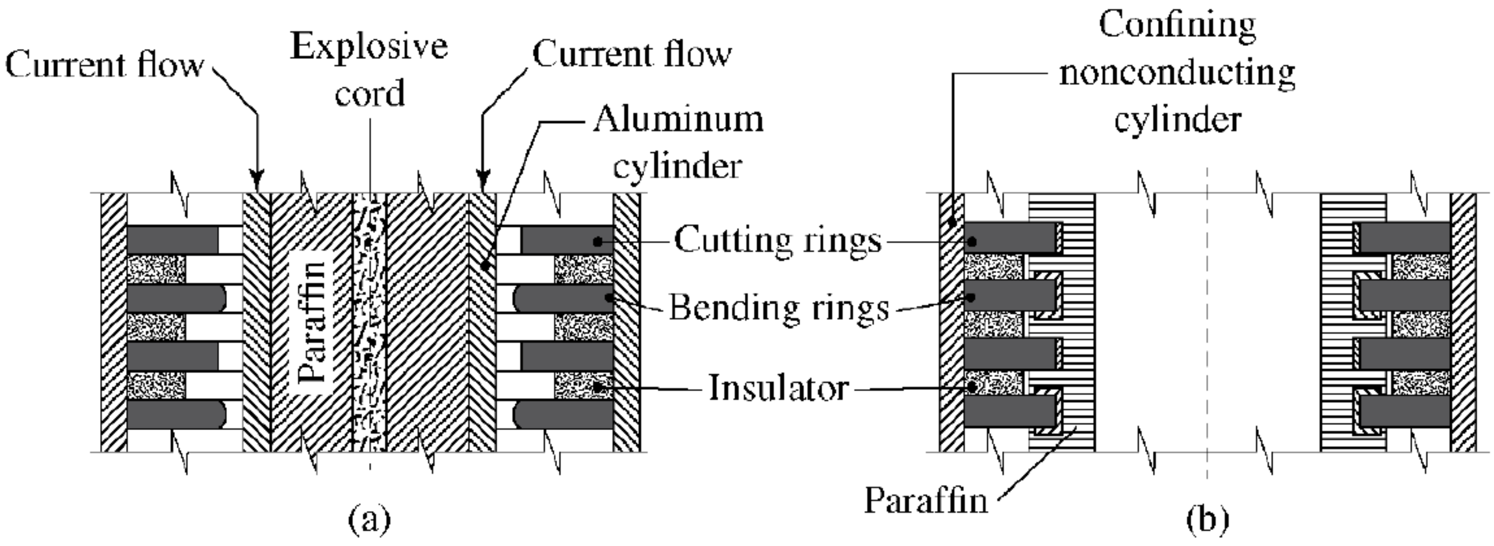
Magnetic vacuum breaker

- The main disadvantages of the mechanical breaker are long opening times and poor repetition rate capability (<50 pps). To overcome these drawbacks, a magnetic vacuum breaker (MVB) was developed where the electrodes are stationary.
- The closing of the switch is initiated by applying a voltage pulse between cathode and trigger electrodes causing current flow and evaporation of the metal coating on the insulator. The metal vapor/plasma bridges the gap between the cathode and anode and causes the closure of the switch.
- The opening of the switch is achieved by energizing the magnet coil. The axial magnetic field thus produced exerts a force on the electrons and makes them traverse a longer path to reach the anode.

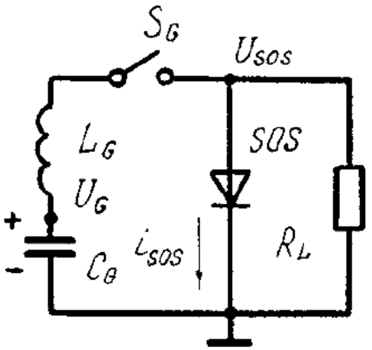


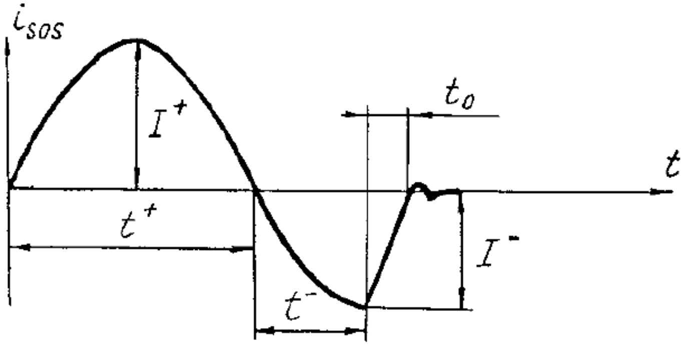
Explosive switch

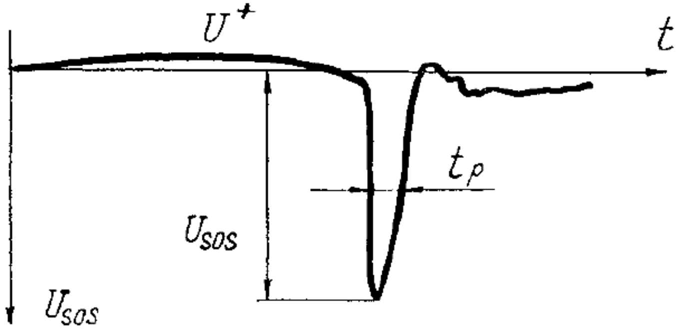
- Opening of the explosive switch is initiated by detonating the explosive. The outward radial pressure cuts the cylinder at the edges of the cutting rings and folds it back onto the bending rings. As a result, the current continues to flow by electrical arcs formed between the rings. The paraffin, which extrudes radially outward, acts as a heat sink, quenches the arc, and interrupts the current.

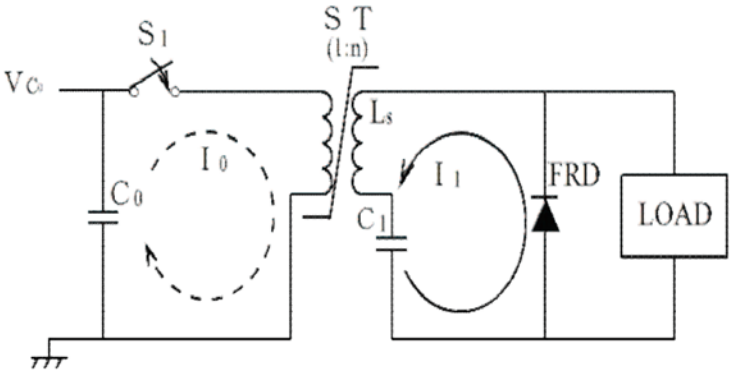


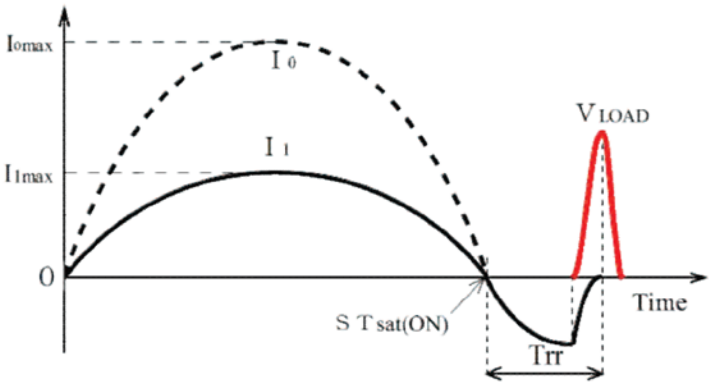
Semiconductor opening switch





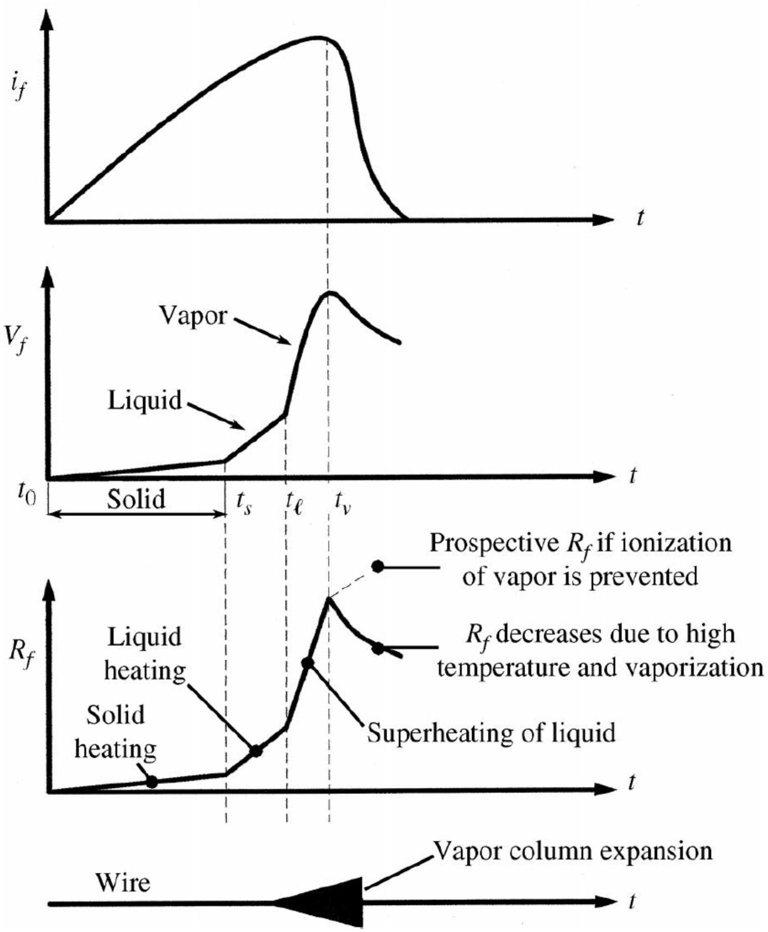




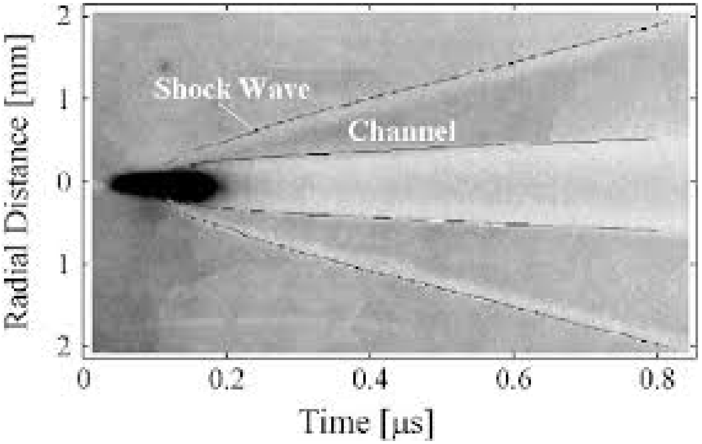


Exploding fuse (wire)

- An exploding fuse switch interrupts the circuit current from the rapid joule heating of the conducting wire or foil, resulting in the vaporization of the foil and sudden jump in resistance.



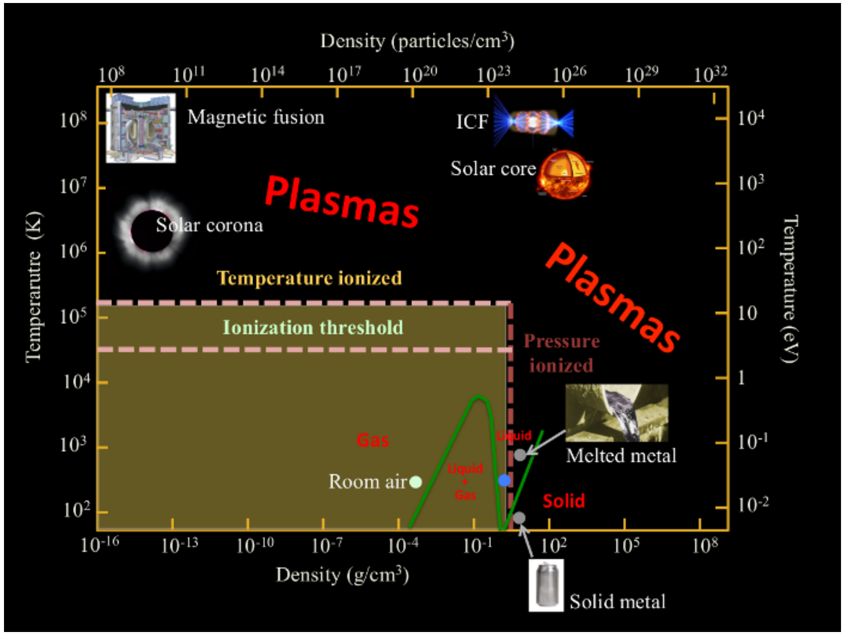
Edward Nairne and his electrical machine, 1783

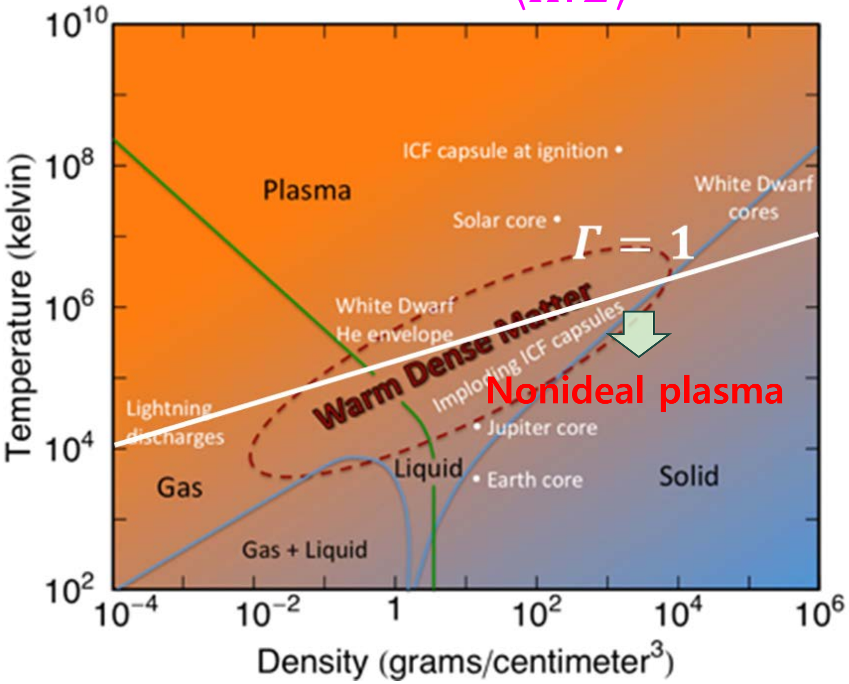


Physics of exploding wire

- Electrical explosion of metal or non-metal wires has long been studied in various research fields from inertial confinement fusion to nano-materials fabrication.
- In particular, it is well known that the exploding wire produces a nonideal, strongly coupled plasma, which is characterized by $\Gamma > 1$, where Γ is the coupling parameter defined as the ratio of the average Coulomb energy between charged particles and the average thermal energy.

$$\Gamma = \frac{\langle P.E \rangle}{\langle K.E \rangle}$$





Nonideal plasmas

- The picture of Debye shielding is valid only if there are enough particles in the charge cloud. Clearly, if there are only one or two particles in the sheath region, Debye shielding would not be a statistically valid concept. We can compute the number of particles in a “Debye sphere”:

$$N_D = n\frac{4}{3}\pi\lambda_D^3$$

Wigner-Seitz radius $a = \sqrt[3]{4\pi n_e/3}$

- Plasma parameter

$$\Lambda = 4\pi n\lambda_D^3 = 3N_D$$

- Coupling parameter

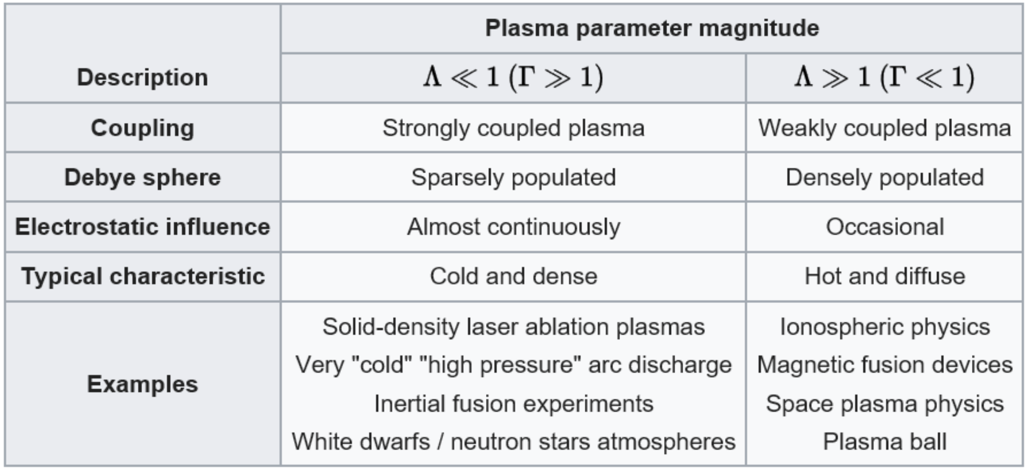
$$\Gamma = \frac{\text{Coulomb energy}}{\text{Thermal energy}} = \frac{q^2/(4\pi\epsilon_0 a)}{kT_e} \sim \Lambda^{-2/3}$$

- Criteria for plasmas:

$$\boxed{\lambda_D \ll L}$$

$$\boxed{N_D \gg 1}$$

$$\boxed{\omega_{pe}\tau_c > 1}$$

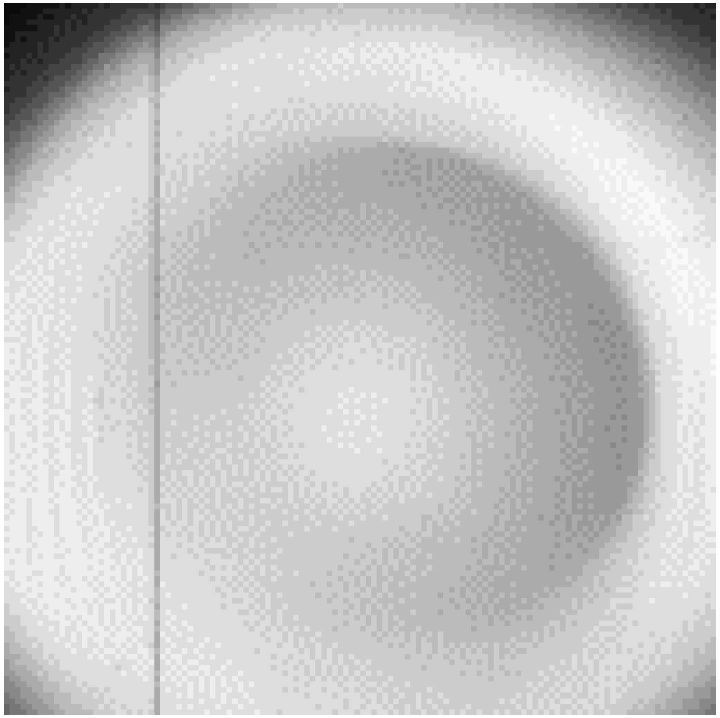


Description	Plasma parameter magnitude	
	$\Lambda \ll 1$ ($\Gamma \gg 1$)	$\Lambda \gg 1$ ($\Gamma \ll 1$)
Coupling	Strongly coupled plasma	Weakly coupled plasma
Debye sphere	Sparsely populated	Densely populated
Electrostatic influence	Almost continuously	Occasional
Typical characteristic	Cold and dense	Hot and diffuse
Examples	Solid-density laser ablation plasmas Very "cold" "high pressure" arc discharge Inertial fusion experiments White dwarfs / neutron stars atmospheres	Ionospheric physics Magnetic fusion devices Space plasma physics Plasma ball

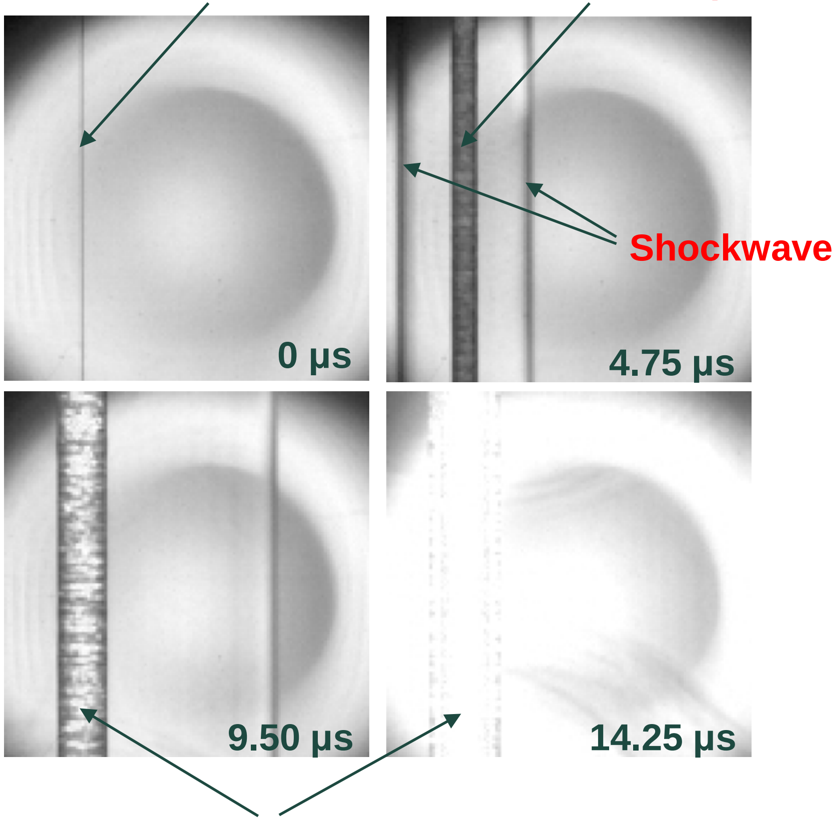
Nonideal plasma formation by wire explosion

- An exploding wire undergoes phase change from solid to plasma state through superheated liquid within tens of us.

Cu wire : ϕ 100 μm @ V_c = 10 kV



Recording = 21,052 fps
Frame interval = 4.75 μs
Exposure = 0.31 μs



Initial wire

Phase transition/expansion

Shockwave

Nonideal plasma

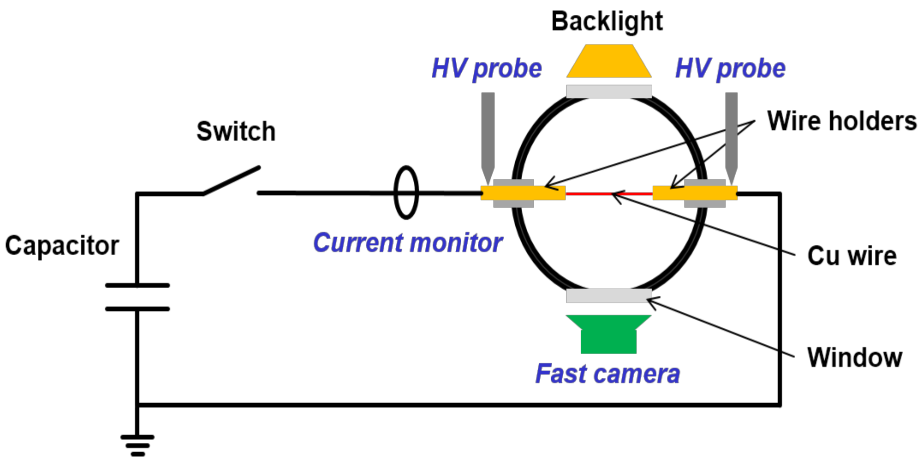
[Optional] Modeling of underwater wire explosion

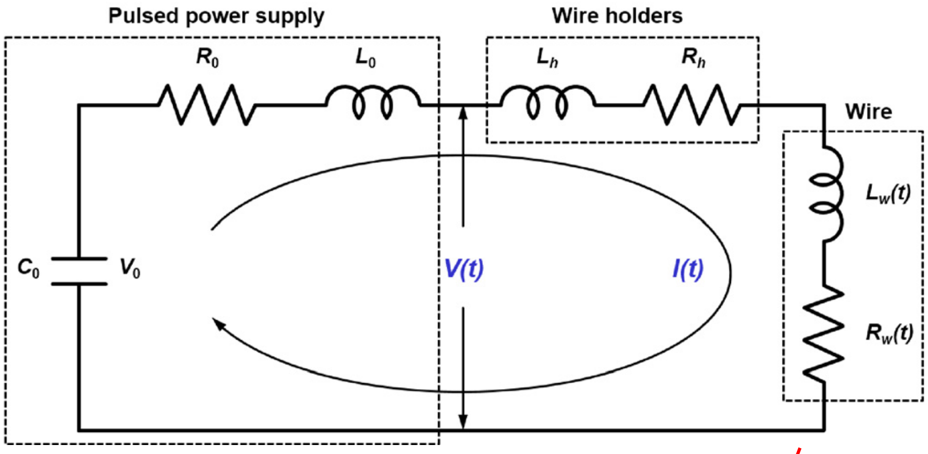
JOURNAL OF APPLIED PHYSICS **120**, 203301 (2016)

Numerical model for electrical explosion of copper wires in water

Kyoung-Jae Chung,[1] Kern Lee,[1] Y. S. Hwang,[1,a)] and Deok-Kyu Kim[2]
[1]*Department of Nuclear Engineering, Seoul National University, Seoul 08826, South Korea*
[2]*Agency for Defense Development, Daejeon 34186, South Korea*

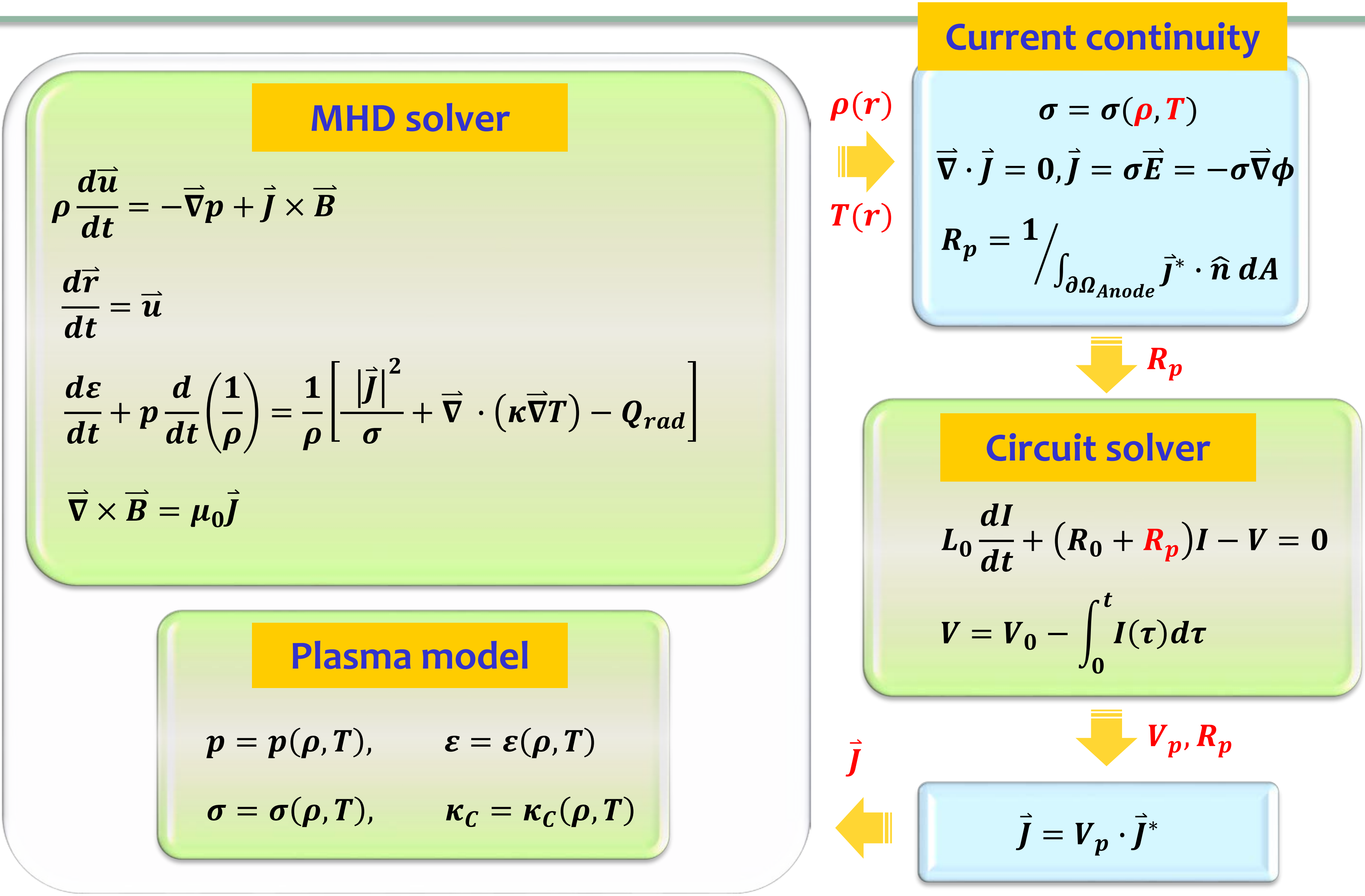
$$V(t) = \left(L_h + L_w(t)\right)\frac{dI(t)}{dt} + \left(R_h + R_w(t) + \frac{dL(t)}{dt}\right)I(t)$$





Exploding wire: time-varying load

Numerical model



MHD solver

$$\rho\frac{d\vec{u}}{dt} = -\vec{\nabla}p + \vec{J}\times\vec{B}$$

$$\frac{d\vec{r}}{dt} = \vec{u}$$

$$\frac{d\varepsilon}{dt} + p\frac{d}{dt}\left(\frac{1}{\rho}\right) = \frac{1}{\rho}\left[\frac{\left|\vec{J}\right|^2}{\sigma} + \vec{\nabla}\cdot\left(\kappa\vec{\nabla}T\right) - Q_{rad}\right]$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J}$$

Plasma model

$$p = p(\rho, T), \qquad \varepsilon = \varepsilon(\rho, T)$$

$$\sigma = \sigma(\rho, T), \qquad \kappa_C = \kappa_C(\rho, T)$$

$\rho(r)$

$T(r)$

Current continuity

$$\sigma = \sigma(\rho, T)$$

$$\vec{\nabla}\cdot\vec{J} = 0, \vec{J} = \sigma\vec{E} = -\sigma\vec{\nabla}\phi$$

$$R_p = 1\Big/\int_{\partial\Omega_{Anode}} \vec{J}^* \cdot \hat{n}\, dA$$

R_p

Circuit solver

$$L_0\frac{dI}{dt} + \left(R_0 + R_p\right)I - V = 0$$

$$V = V_0 - \int_0^t I(\tau)d\tau$$

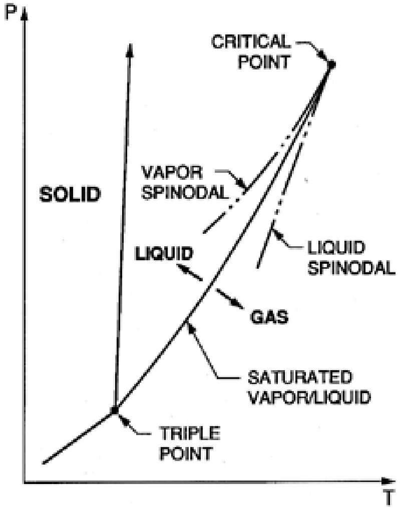
V_p, R_p

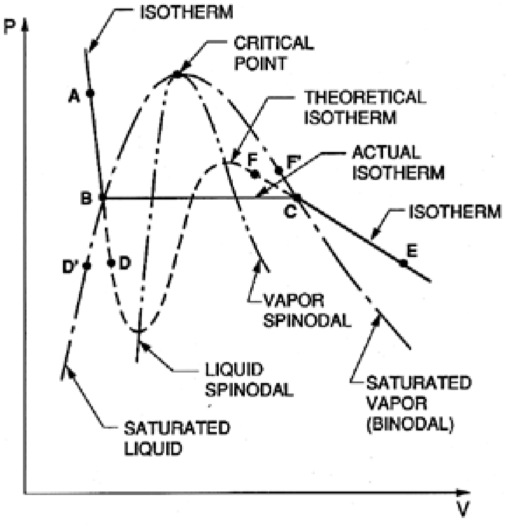
$$\vec{J} = V_p \cdot \vec{J}^*$$

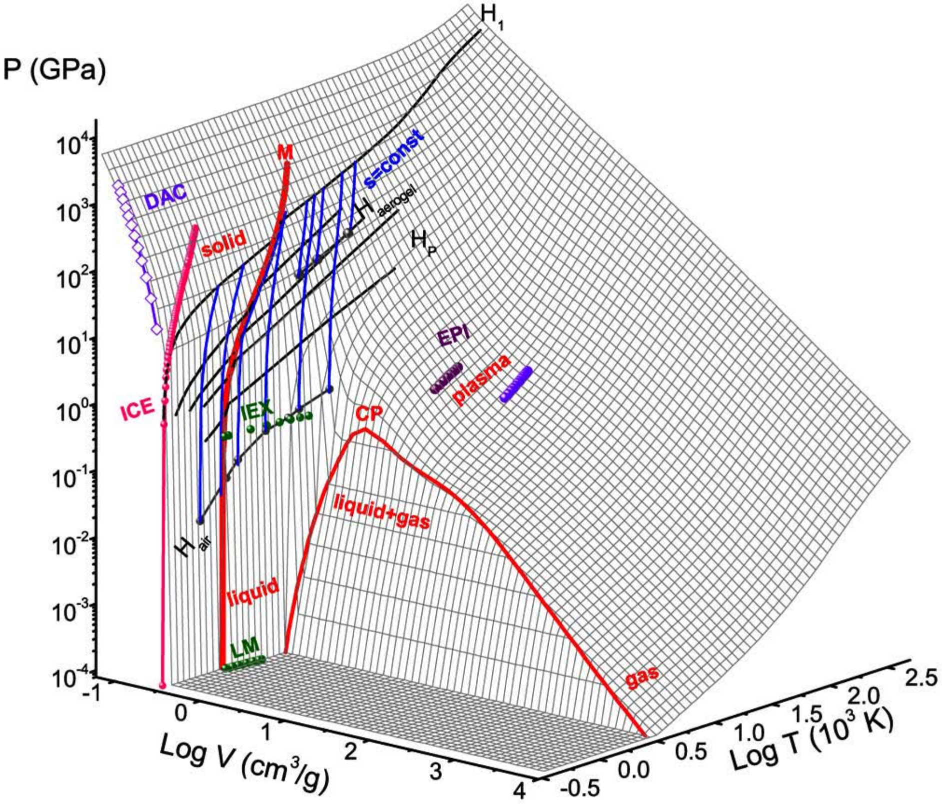
$\vec{J}$

Equation of state for metal

- Since an exploding wire heated by rapidly rising current pulse undergoes huge changes in its thermodynamic variables in the phase plane, the wide-range EOS data including the liquid-vapor phase transition are needed for the precise modeling of the wire explosion system.



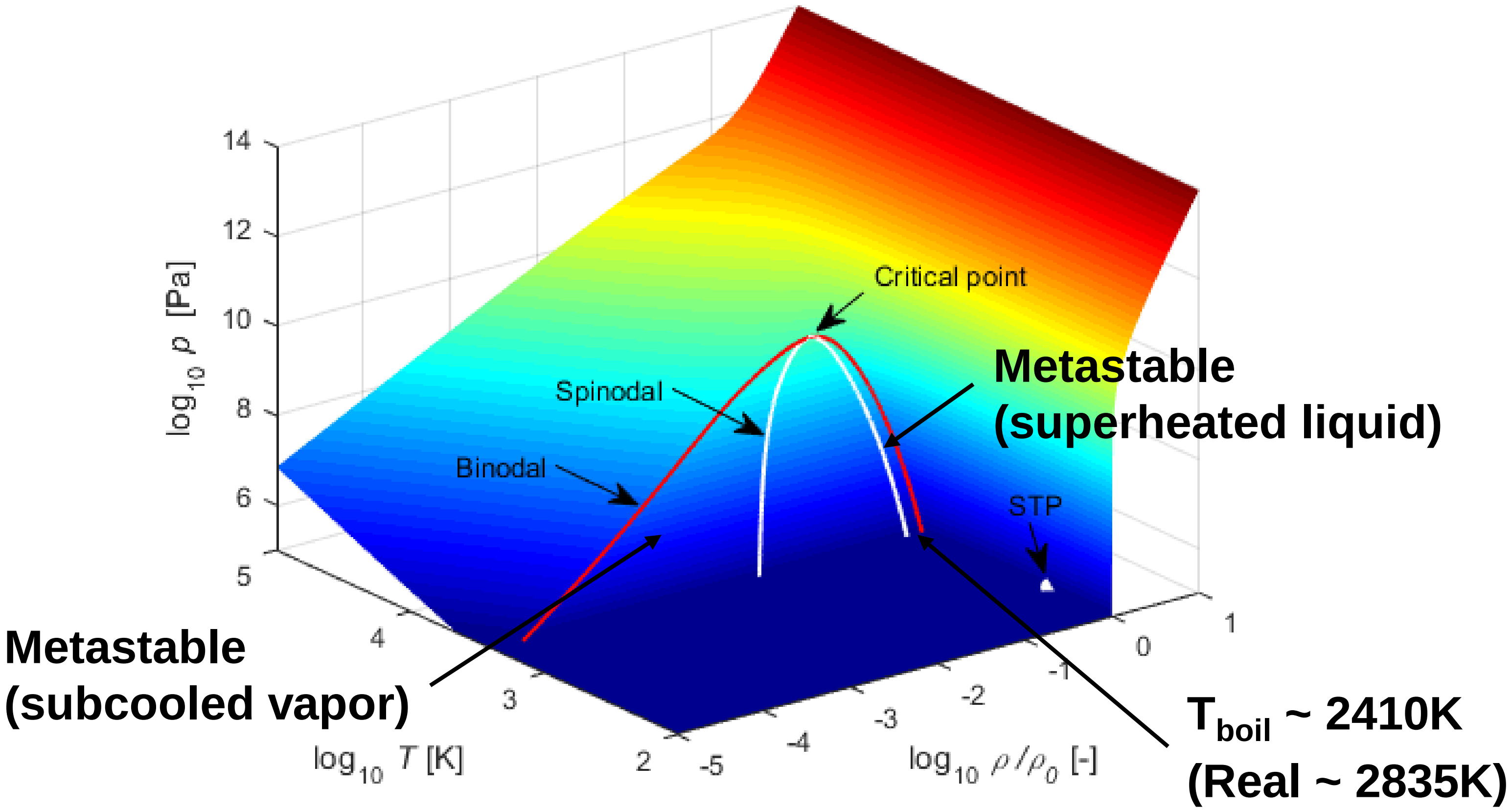




I. V. Lomonosov, Laser and Particle Beams 25, 567 (2007)

Quotidian equation of state (QEOS)

- An approximate method such as “quotidian EOS (QEOS)” developed by More et al. has been widely used for the hydrodynamic calculation.



Metastable (superheated liquid)

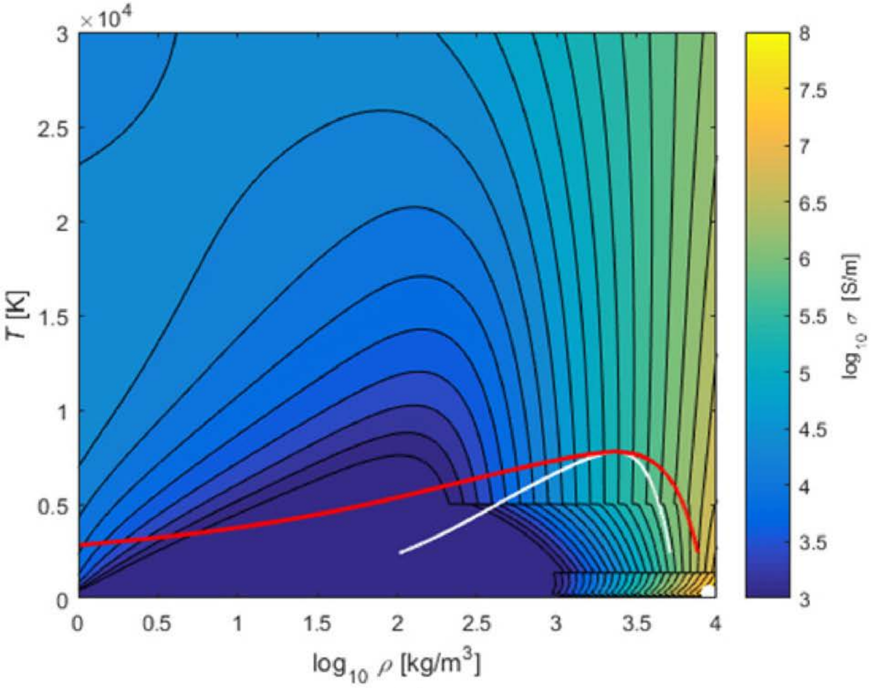
Metastable (subcooled vapor)

T_{boil} ~ 2410K (Real ~ 2835K)

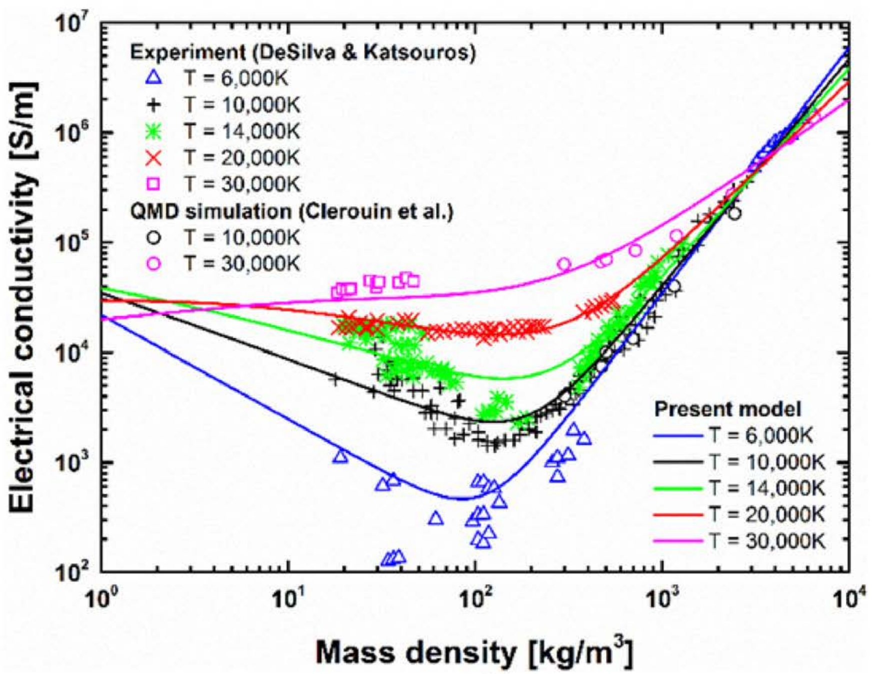
*R. M. More et al., Phys. Fluids 31, 3059 (1988)

Wide-range conductivity model

- Since the heating and phase transformation of the wire are totally governed by the Joule heating mechanism, an appropriate electrical conductivity model is crucial for the modeling of the exploding wire system. There is no single theory for the electrical conductivity of materials covering wide-range from solid to plasma state. → approximate semi-empirical model



(a)

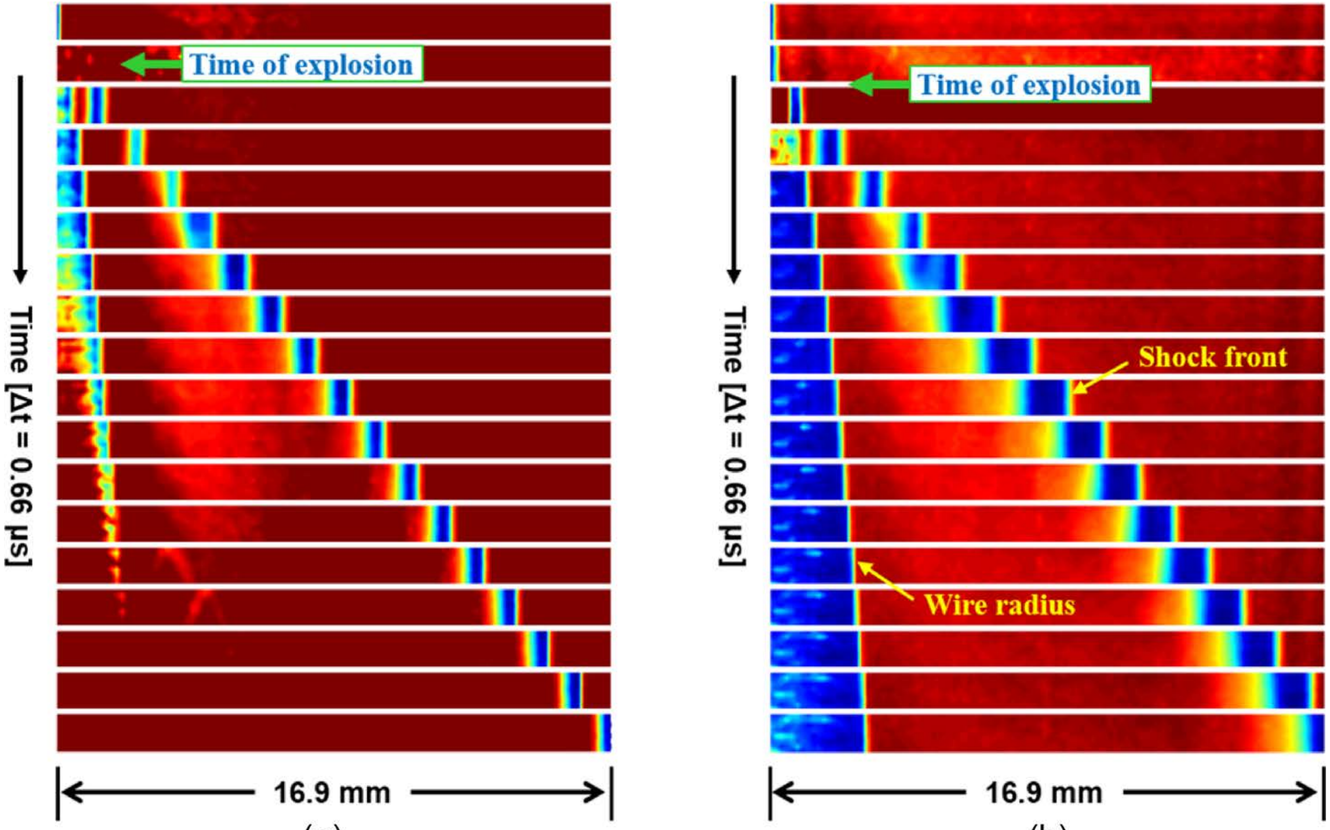


(b)

* J. Stephens et al., Phys. Rev. E 89, 053102 (2014)
** A. W. Dasilva et al., Phys. Rev. E 57, 5945 (1998)
*** J. Clerouin et al., Phys. Rev. B 71, 064203 (2005)

Shock wave generation by wire explosion

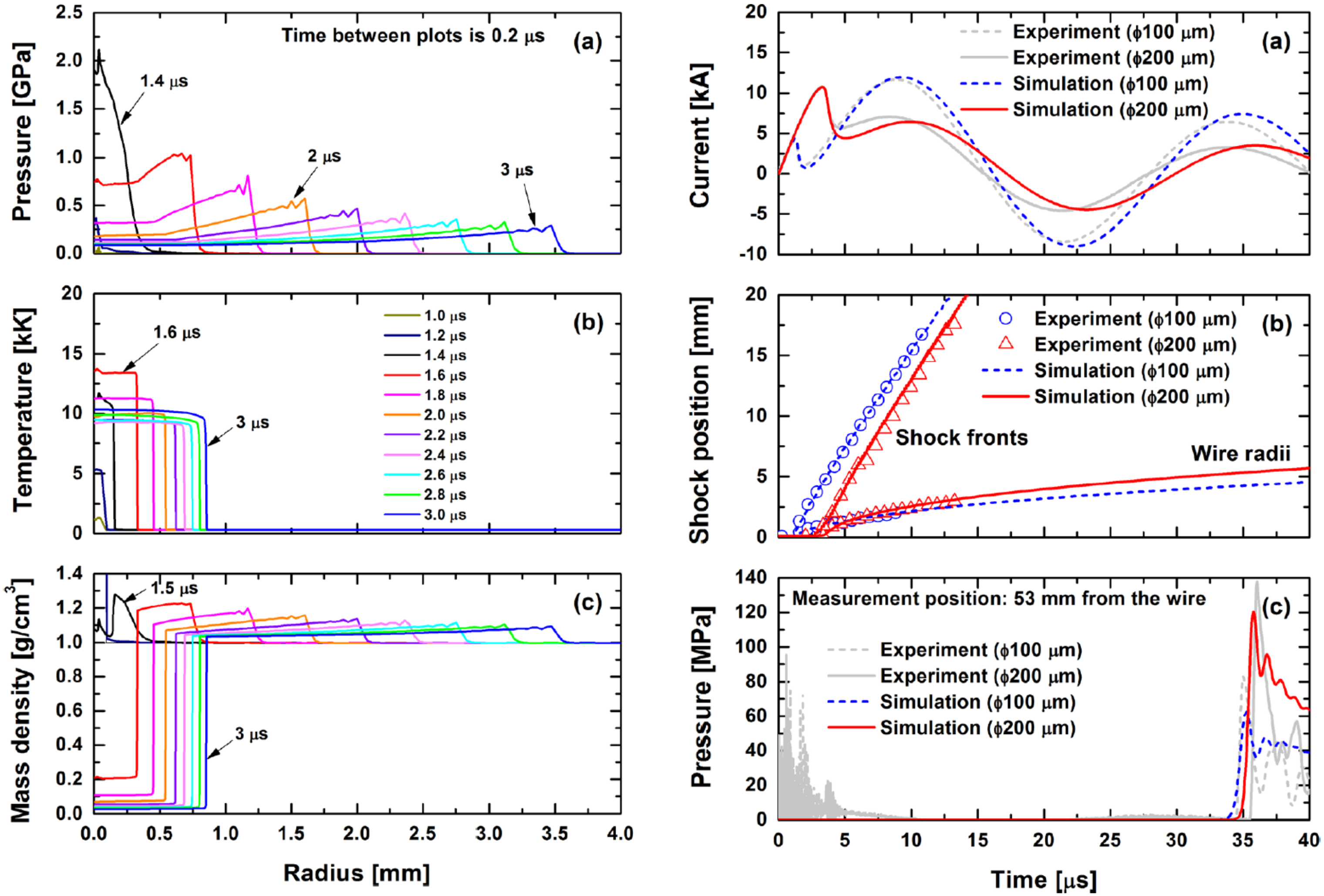
- A strong shock wave is generated by rapid expansion of metal wire, especially during the liquid-vapor phase change.



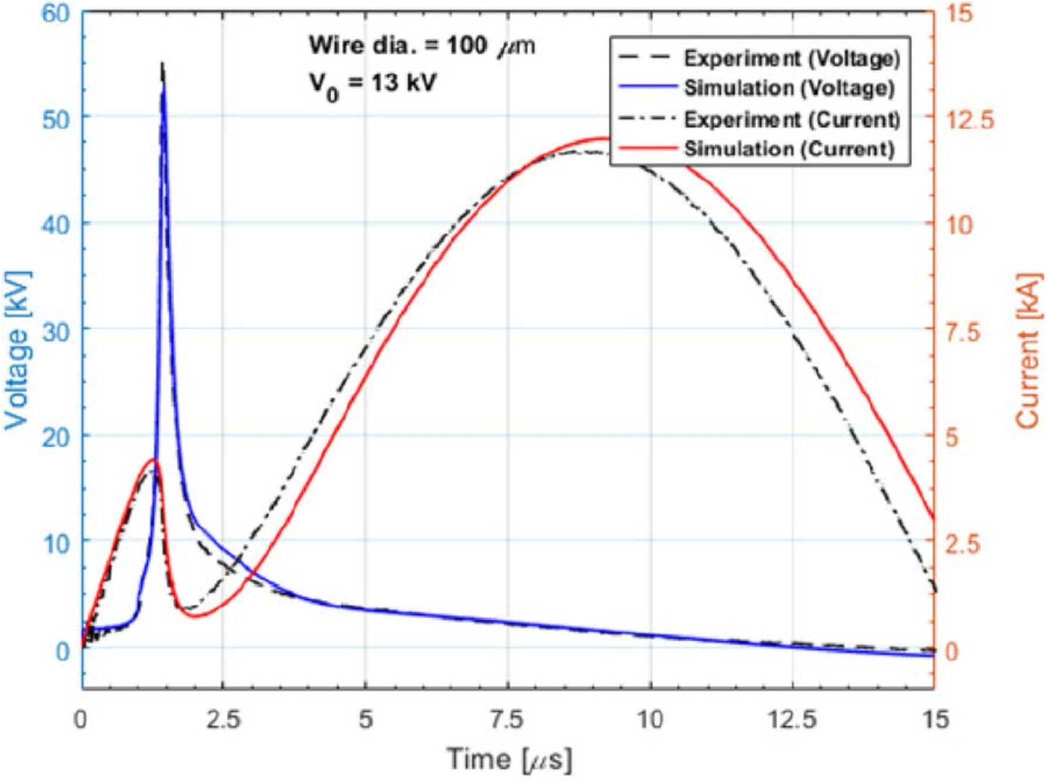
(a) (b)

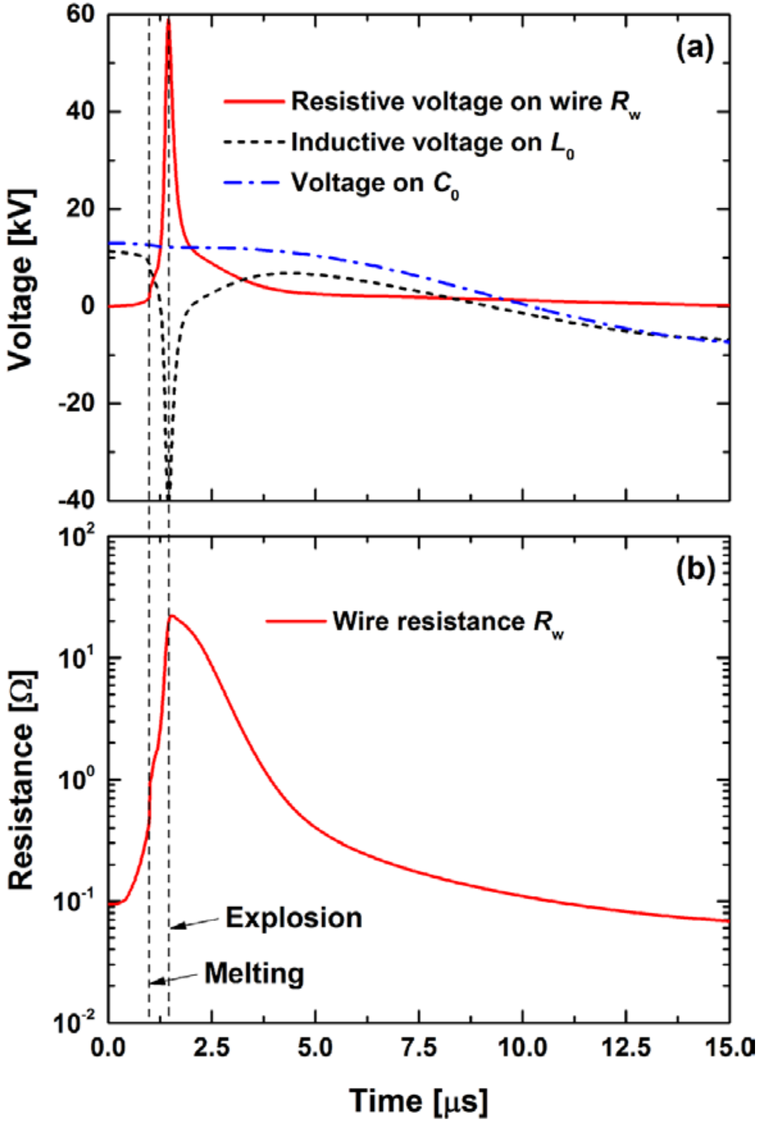
Cu wire : ϕ 100 μm @ V_c = 13 kV **Cu wire : ϕ 200 μm @ V_c = 13 kV**

Shock wave generation by wire explosion



Current-voltage waveforms

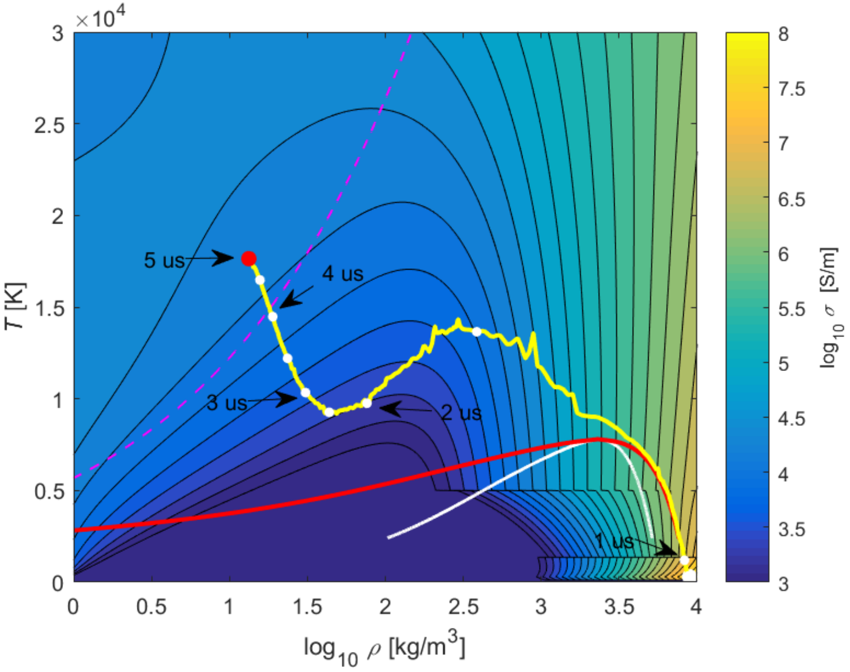


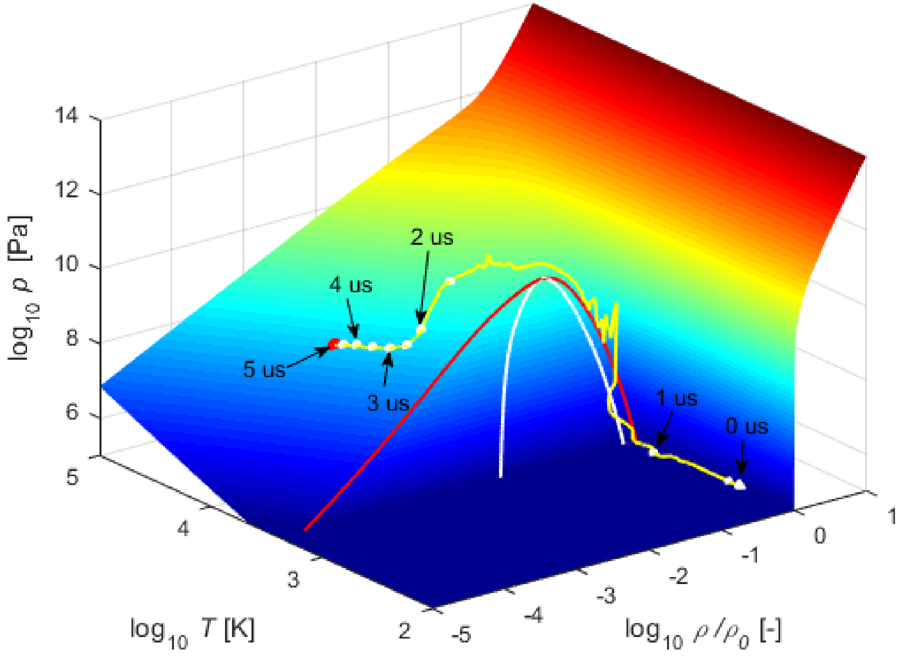


Behavior of exploding wire

- **Cu wire - $(\phi)100\ \mu m \times (L)40\ mm$**
- **Charging voltage (V_0) = 13 kV**

($\Delta t = 0.5\ \mu s$ b/w each circle)





Current restrike

- The metal vapor starts expanding and at some time when the mean free path in the metal vapor is favorable, the breakdown occurs in the metal vapor, resulting in a restrike, when the current increases again.