Inverse Z-Pinch Experiment

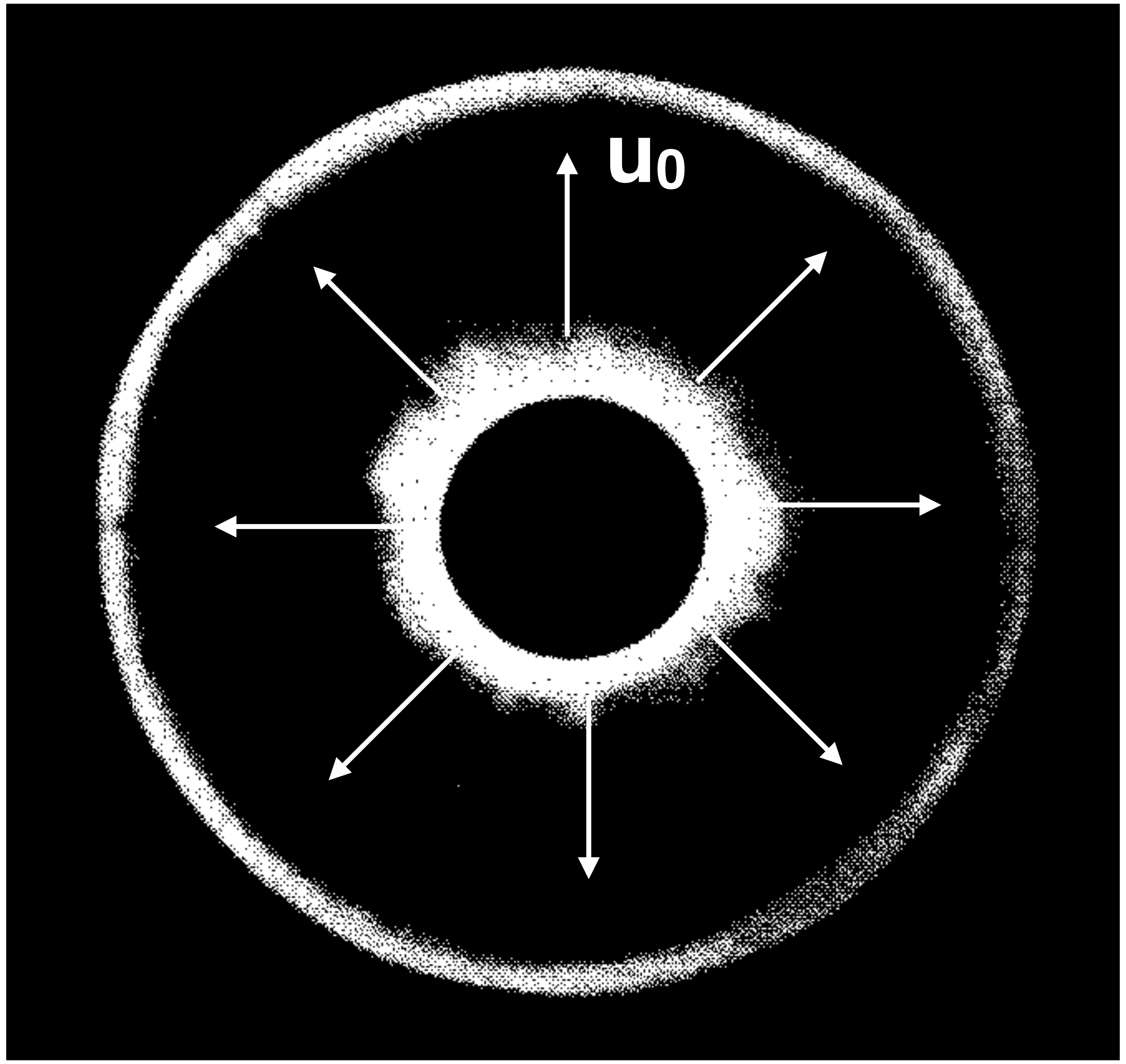
AP 4018
Columbia University

Objectives

- Measure the speed, u_0, of an outward moving magnetohydrodynamic shock wave

- Compare speed with nonlinear MHD model

u_0 is shock speed



"Shock and Current Layer Structure in an Electromagnetic Shock Tube," George C. Vlases, Phys Fluids 10, 2351 (1967); https://doi.org/10.1063/1.1762043

Introductory Reading

- George Vlases studied the inverse Z-pinch for his 1963 PhD thesis at CalTech:

  Experiments in a cylindrical magnetic shock tube, Dissertation (Ph.D.), CalTech; https://resolver.caltech.edu/CaltechTHESIS:10092012-110749746

- Excellent summary:

  "Shock and Current Layer Structure in an *Electromagnetic Shock Tube," George C. Vlases,* Phys Fluids 10, 2351 (1967); https://doi.org/10.1063/1.1762043

- First discovered by Prof. Hans Wolfgang Liepmann (1914-2009) and Vlases in 1961. President Ronald Reagan awarded Liepmann the National Medal of Science in 1986.

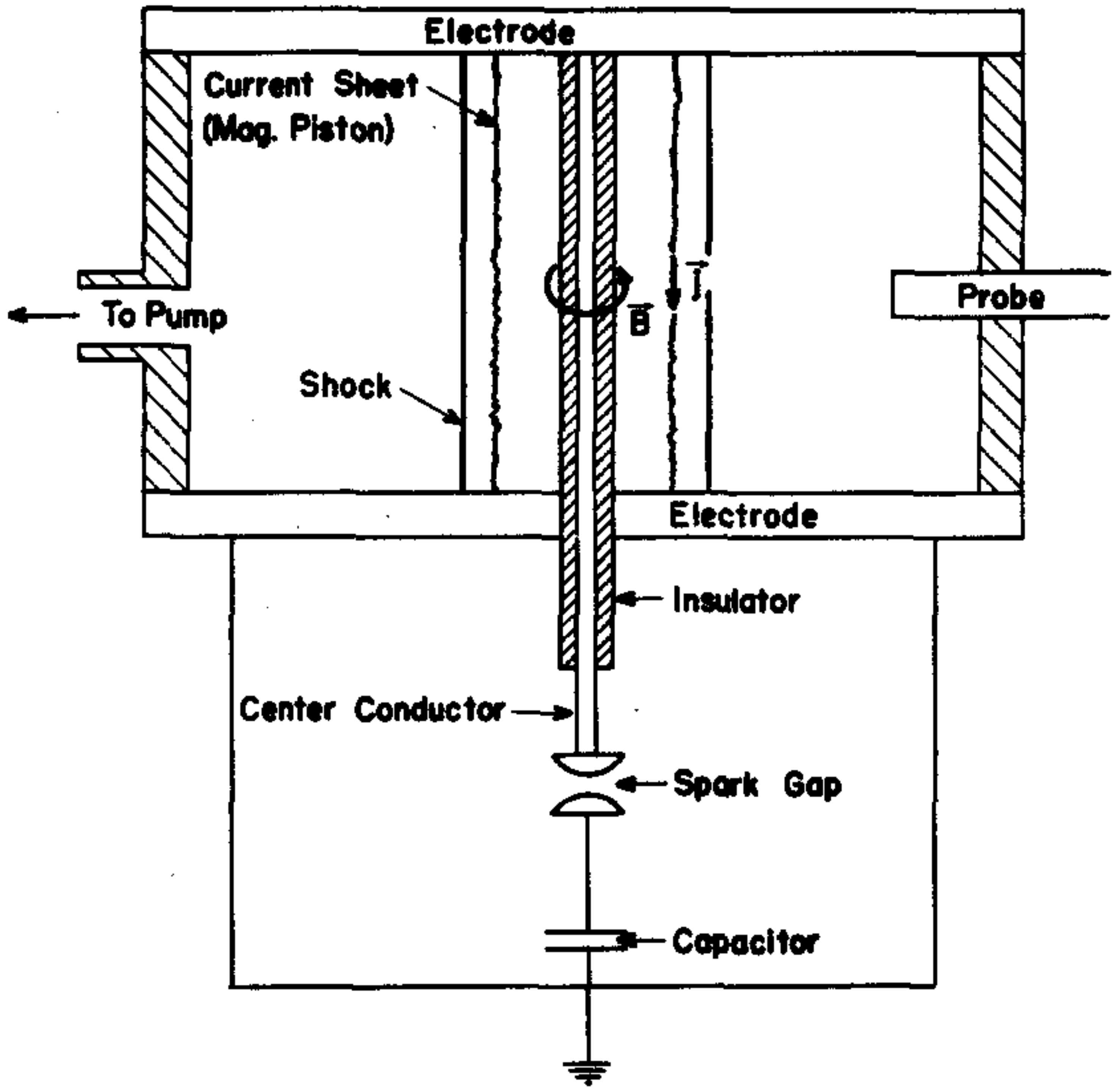


FIG. 1. Schematic diagram of apparatus.

"Magnetically Driven Cylindrical Shock Waves,"
H. W. Liepmann, and G. Vlases, *Phys Fluids* 4, 927 (1961);
https://doi.org/10.1063/1.1706428

Speed of Shock

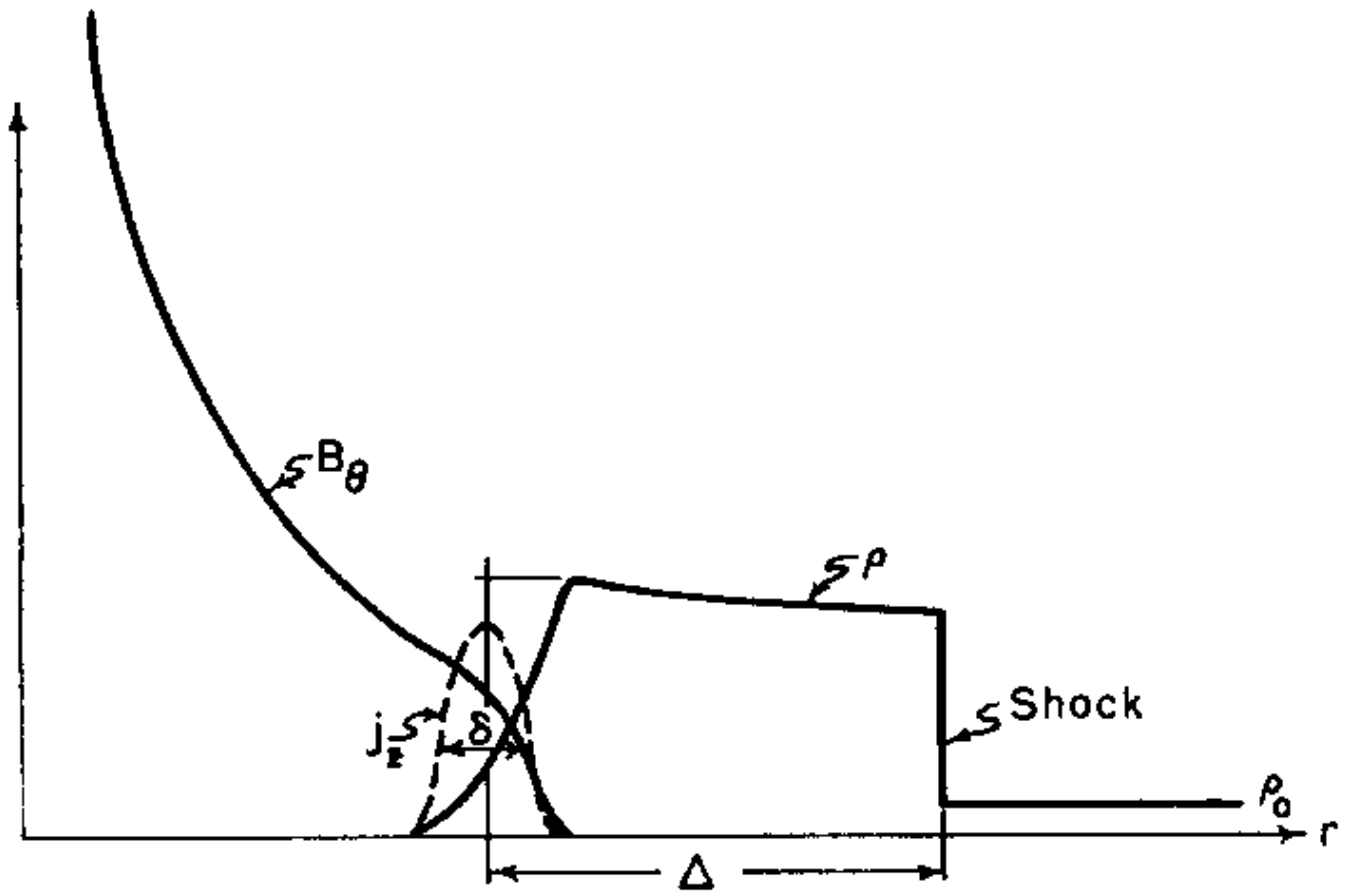


FIG. 1. Idealized flow model. $\delta \sim (t/\mu\sigma)^{\frac{1}{2}} \sim (r_c/u_0\mu\sigma)^{\frac{1}{2}}$; $\Delta \sim r_s/2\eta$, $\Delta/\delta \sim (\mu\sigma u_0 R)^{\frac{1}{2}}/\eta$.

Speed is nearly constant!

for the current to reach its first maximum, the shock location is given by[12]

$$r \approx u_0 t, \tag{3}$$

where u_0 is the characteristic snowplow velocity,

$$u_0 = \left\{ \frac{V_0^2}{L^2} \frac{\mu}{8\pi^2 \rho_0} \right\}^{\frac{1}{4}}. \tag{4}$$

(MKS Units)

where V_0 is the voltage, L is the inductance, and ρ_0 is the mass density of the gas

Nonlinear MHD (with Similarity Solution)

$$r(t) = u_0 t$$

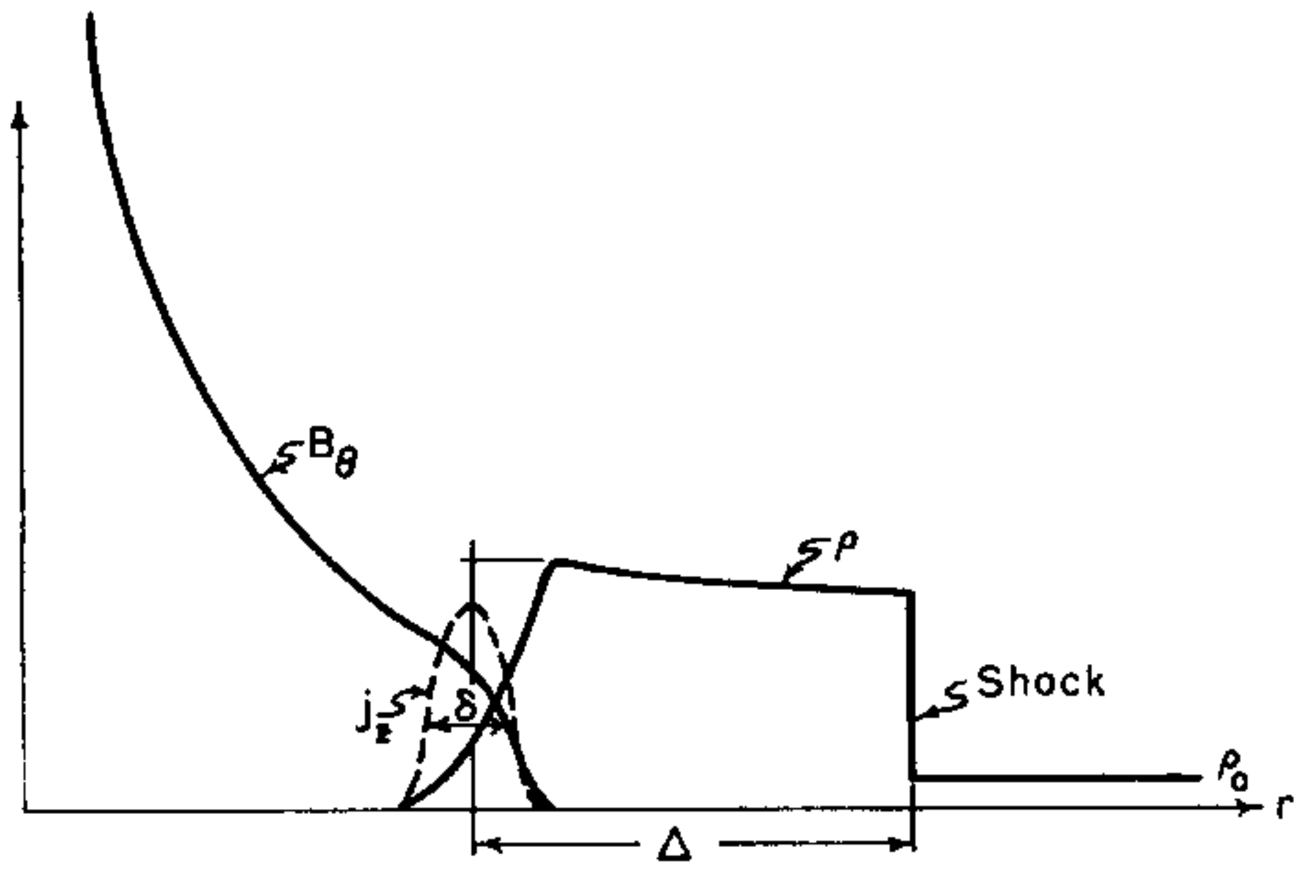


FIG. 1. Idealized flow model. $\delta \sim (t/\mu\sigma)^{\frac{1}{2}} \sim (r_c/u_0\mu\sigma)^{\frac{1}{2}}$; $\Delta \sim r_s/2\eta$, $\Delta/\delta \sim (\mu\sigma u_0 R)^{\frac{1}{2}}/\eta$.

$$\frac{d}{dt}\left(M\frac{dr}{dt}\right) = \text{Force} = \Delta\text{Pressure} \cdot (2\pi r h)$$

$$\Delta\text{Pressure} = \frac{B^2(r)}{2\mu_0} - P_{gas}$$

$$M(r) = \pi r^2 h \rho_0$$

$$B(r) = \frac{\mu_0 I(t)}{2\pi r} \approx \frac{\mu_0 t \dot{I}}{2\pi r}$$

Procedure

- This experiment has one procedure, repeated for different gas and pressures.
- For each condition:

1. Launch an outward moving shock wave
2. Measure magnetic field vs. time at a movable probe
3. Move probe to different radial positions (and measure magnetic field)
4. Determine when the shock wave passes the probe's position
5. Calculate shock speed from $r \approx u_0 t$

Key Physics: Magnetic Pressure

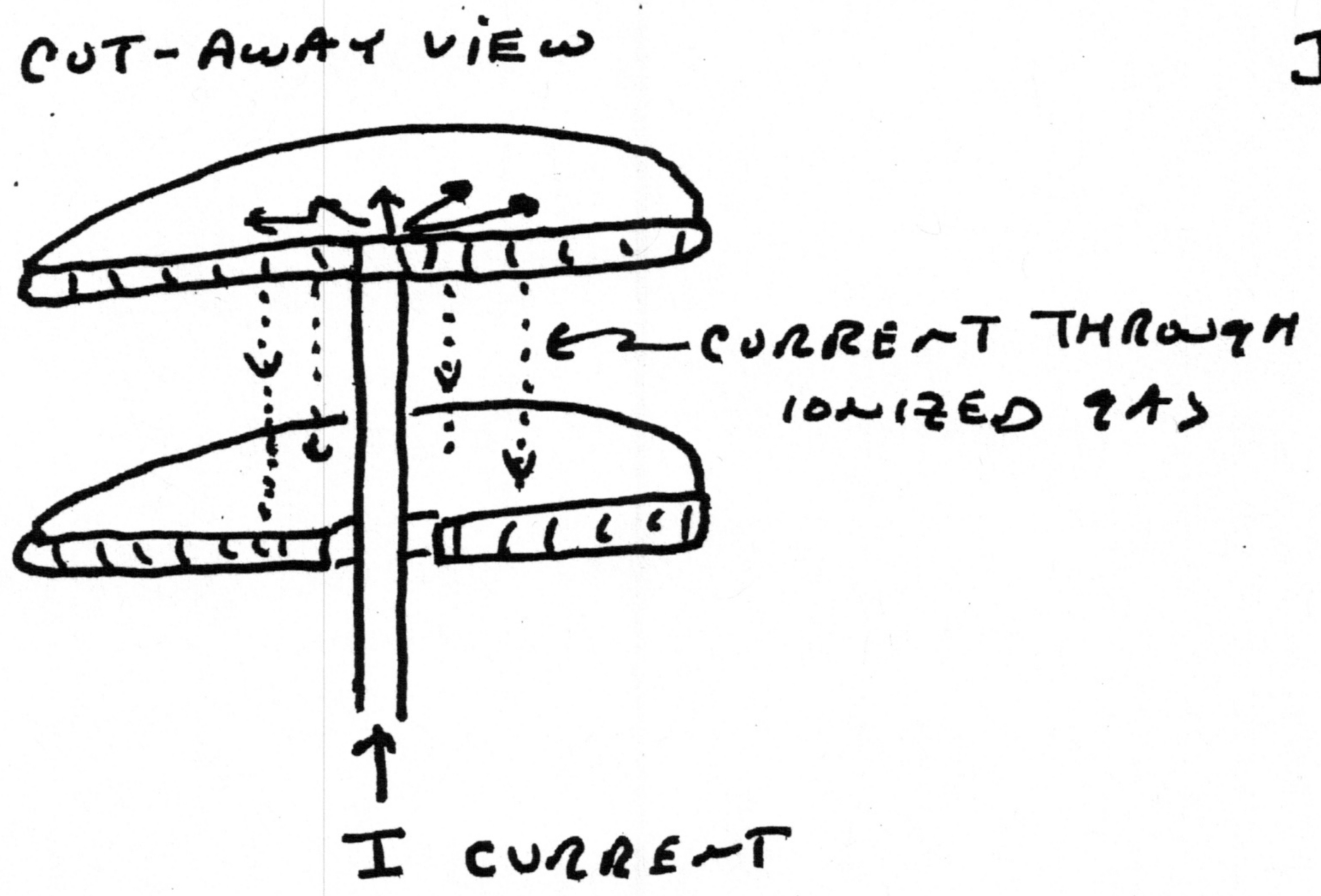
THE KEY PHYSICS OF THIS EXPERIMENT IS THE CREATION OF A LARGE "PRESSURE" GRADIENT THAT DRIVES THE EXPLODING SHOCK WAVE. THIS PRESSURE DIFFERENCE IS CREATED BY A RAPIDLY CHANGING MAGNETIC FIELD.

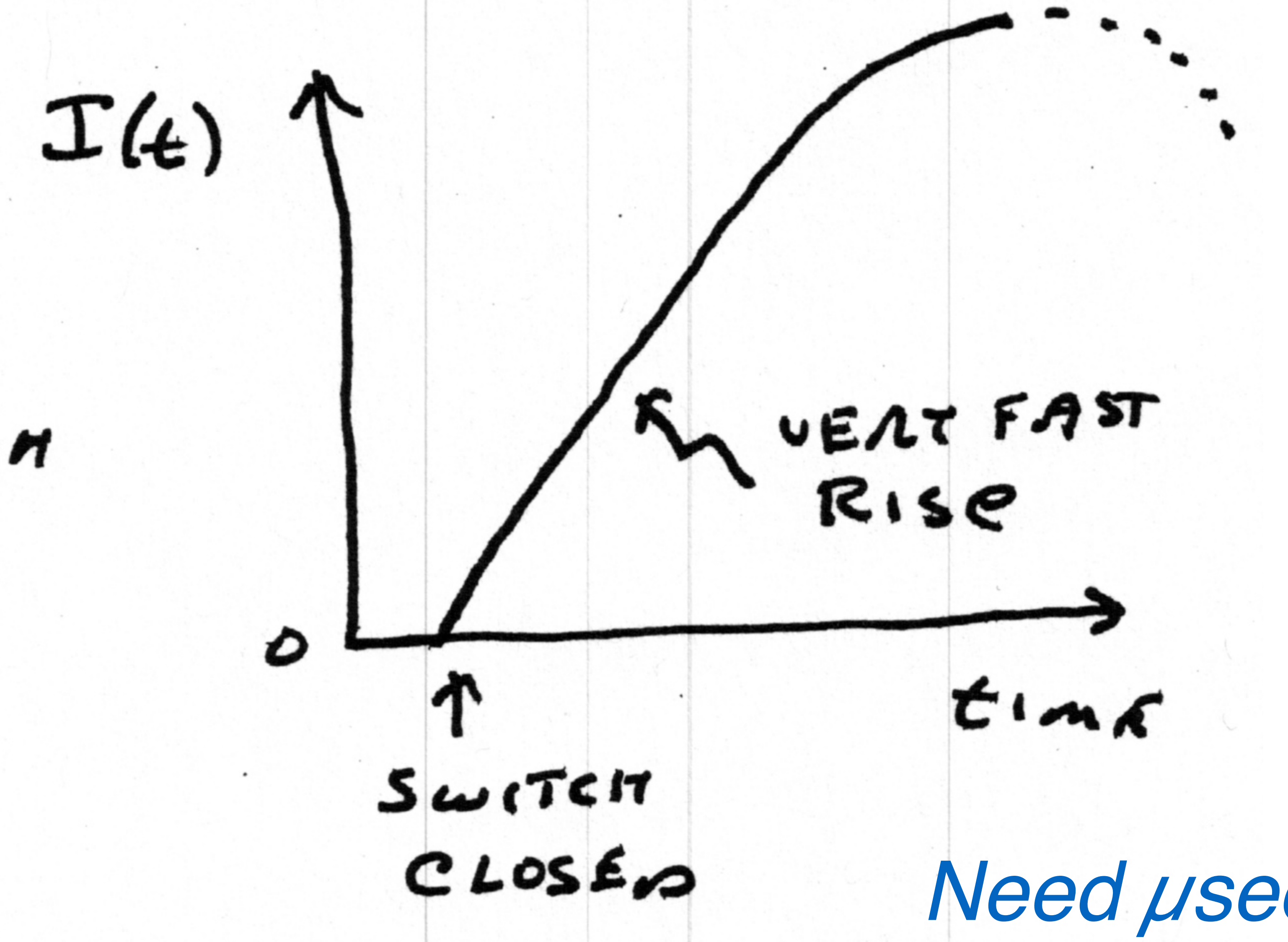
$$\text{TOTAL PRESSURE} = \frac{B^2}{2\mu_0} + P_{GAS}$$

↑ MAGNETIC PRESSURE

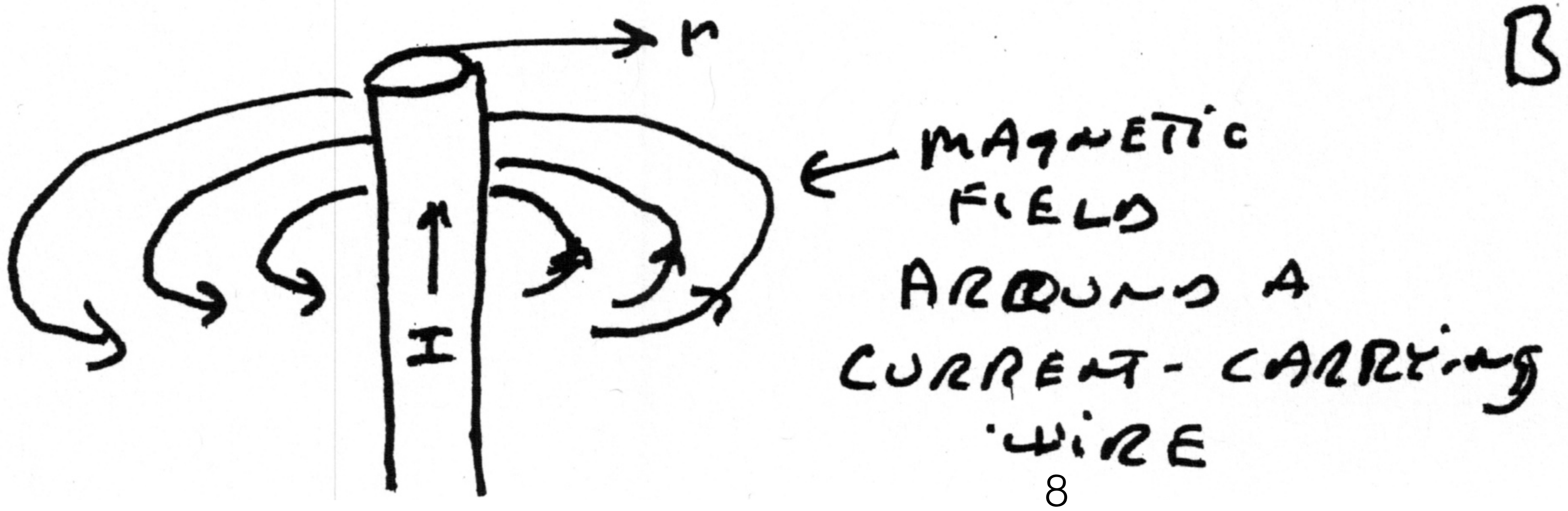
↑ GAS PRESSURE

How the Inverse Z-Pinch Works





Need μsec resolution

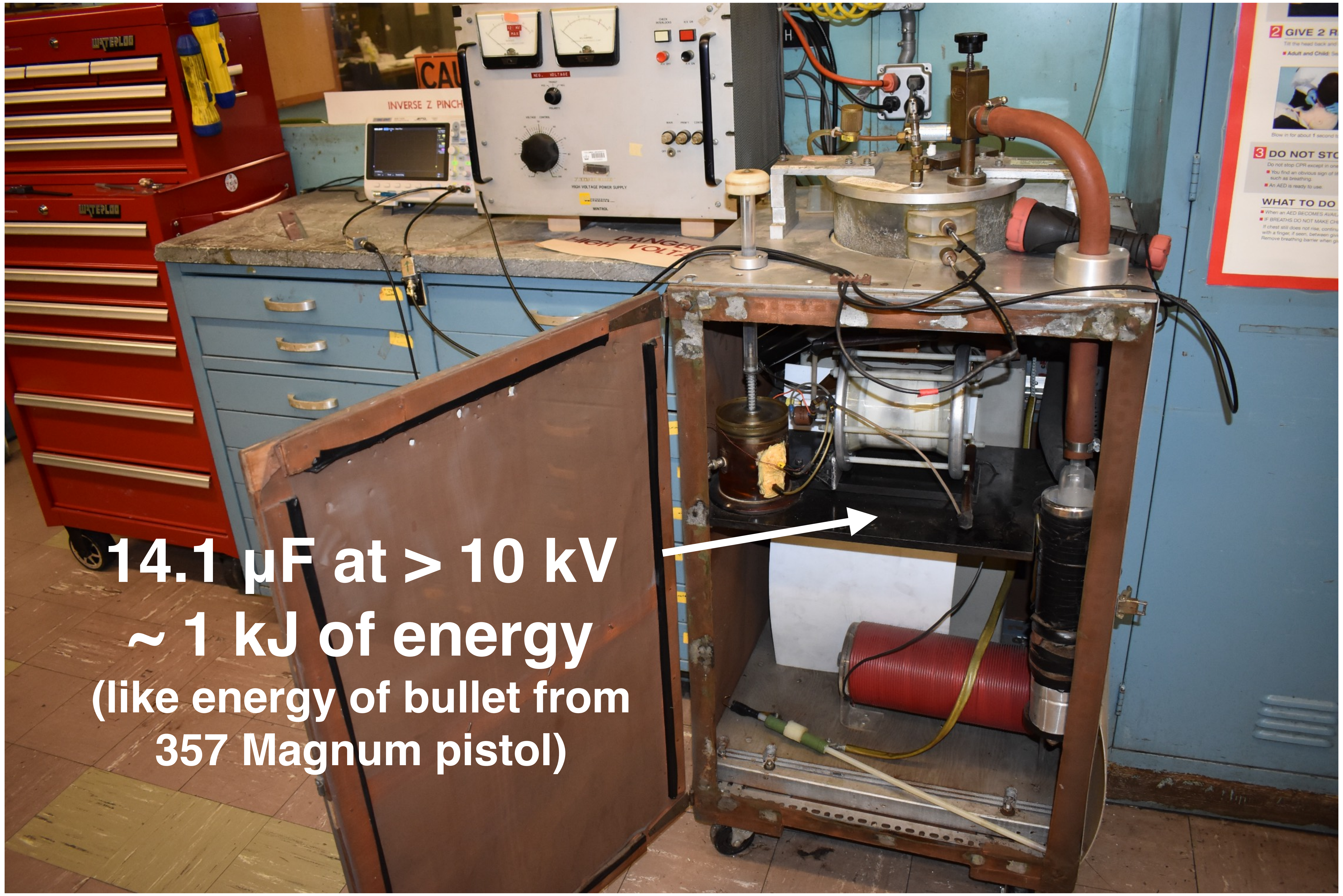


$$B(r) = \frac{I\mu_0}{2\pi r}$$

so

$$\frac{B^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 r^2}$$

High Voltage Pulsed Power



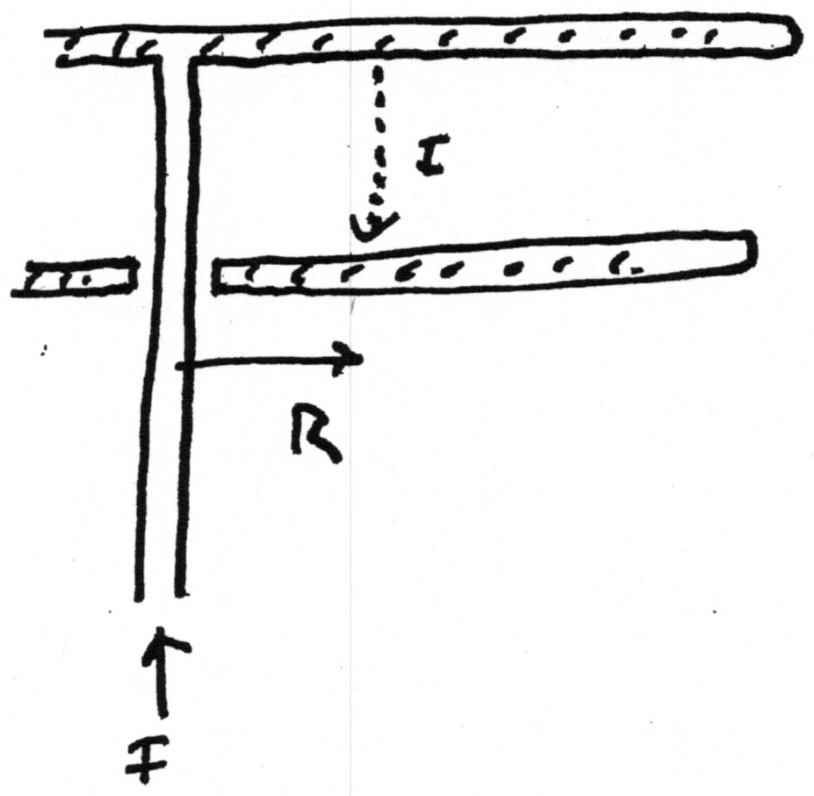
How the Inverse Z-Pinch Works

A Z-PINCH WORKS BY CREATING A CYLINDRICALLY-SYMMETRIC "RING OF CURRENT" THAT SURROUNDS THE CENTRAL CONDUCTOR. TO A REASONABLE APPROXIMATION, THE CURRENT FLOWING THROUGH THE CENTRAL CONDUCTOR ALSO FLOWS BACK THROUGH THE CYLINDRICAL CURRENT SHEET.

THIS CREATES A PRESSURE JUMP THAT DRIVES THE CURRENT SHEET OUTWARD IN RADIUS.

THE CURRENT ALSO IONIZES (ALMOST) ALL OF THE GAS.

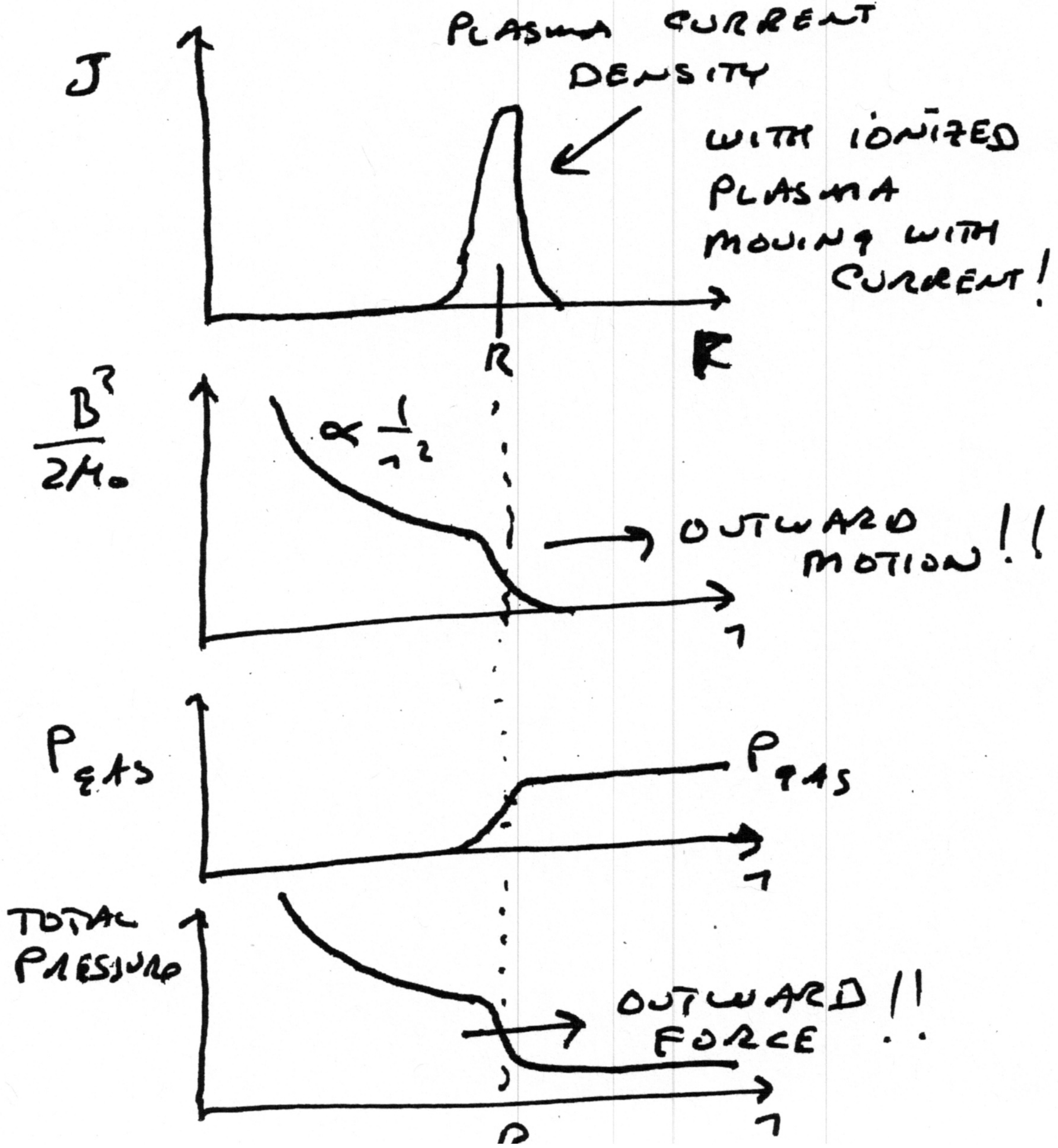
THIS IS CALLED A "SNOW PLOW"!



RADIAL LOCATION OF CURRENT RING ≡ R(t)

IF $\left.\frac{B^2}{2\mu_0}\right|_R > P_{gas}$

THEN CURRENT SHEET MOVES OUTWARD FAST!

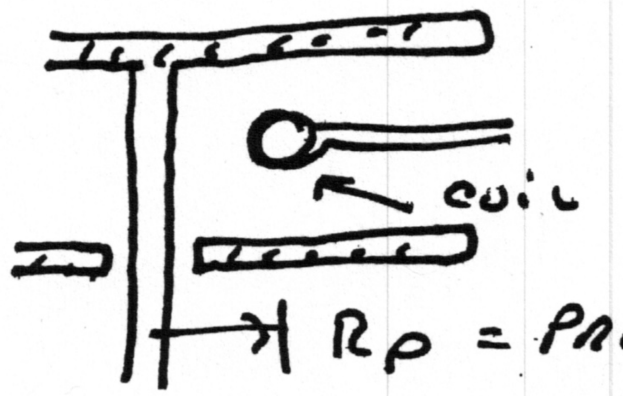


What Do You Measure?

1. GAS PRESSURE (AND TYPE OF GAS, Ar, He)
2. CURRENT vs TIME $I(t)$
3. MAGNETIC FIELD AT DIFFERENT RADII vs TIME $B(r, t)$

What Do You Measure?

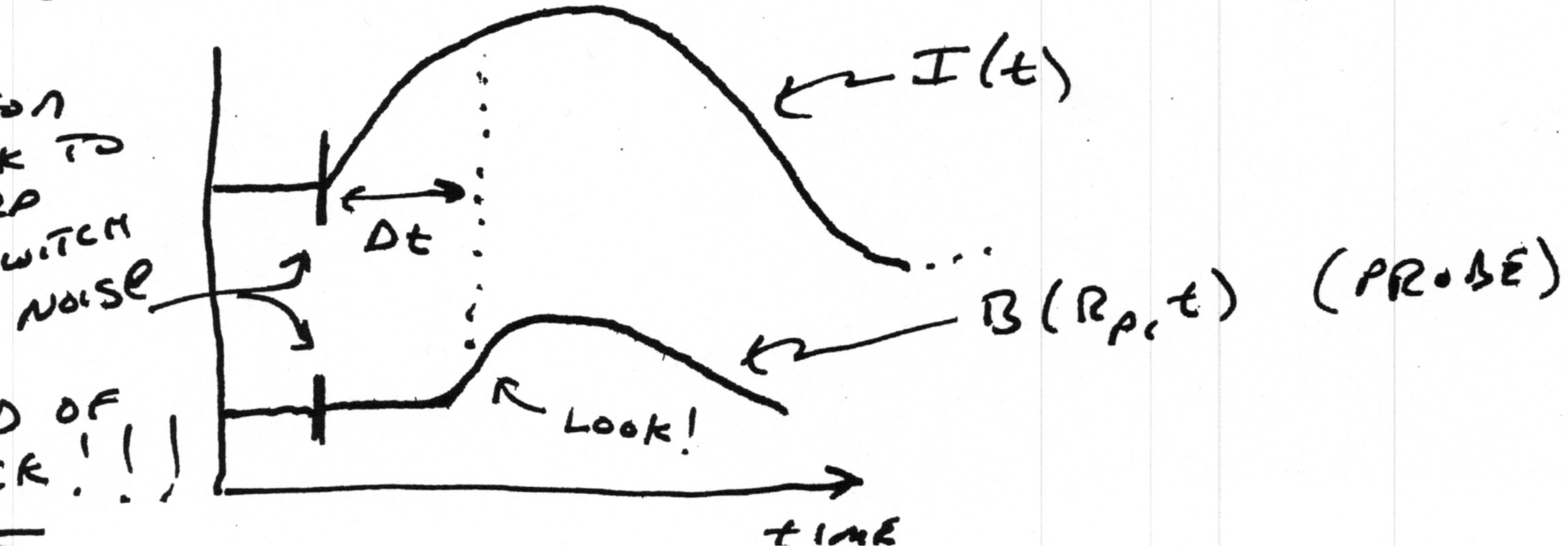
- $I(t)$ and $B(r,t)$ are measured with small coils of wire and passive RC integrators. (See notes.)
- To measure shock, you use a small movable probe inside chamber. The probe must be oriented with coil in the horizontal direction:



- Best: measure $I(t)$ and $B(R_p,t)$ at same time using high speed scope.

- Determine: when does shock reach probe location at $r = R_p$?

Δt = time for shock to reach R_p



$$\frac{R_p}{\Delta t} = \text{speed of shock!!!}$$

Hints and Advice

- MAKE YOUR *FIRST* MEASUREMENTS WITH *ARGON* AT RELATIVELY *HIGH* VOLTAGE/CURRENT. THIS WILL MAKE THE EASIEST SHOCKS TO MEASURE.
- ADJUST YOUR SCOPE TO FOCUS ("ZOOM IN") ON THE INITIAL RISE OF THE CURRENT. THIS IS THE ONLY TIME WHEN A SIMPLE THEORY CAN BE USED TO INTERPRET YOUR RESULTS.
- ALTHOUGH YOU SHOULD MAKE JUST A FEW SIMULTANEOUS MEASUREMENTS OF TWO PROBES, $B(R_{p_1}, t)$ & $B(R_{p_2}, t)$, *MOST* OF YOUR MEASURENTS WILL RECORD $I(t)$ AND $B(R_p, t)$ AS YOU GRADUALLY MOVE R_p.
- ADJUST THE *VERTICAL* SCALES OF YOUR SCOPE SO THAT YOU CAN ALWAYS MEASURE $B(R_p, t)$. AS R_p INCREASES, $B(R_p)$ *DECREASES* AS $1/R_p$.

From the original “discovery”…

Magnetically Driven Cylindrical Shock Waves

H. W. Liepmann and G. Vlases
California Institute of Technology, Pasadena, California
(Received April 6, 1961)

"Magnetically Driven Cylindrical Shock Waves,"
H. W. Liepmann, and G. Vlases, *Phys Fluids* 4, 927 (1961);
https://doi.org/10.1063/1.1706428

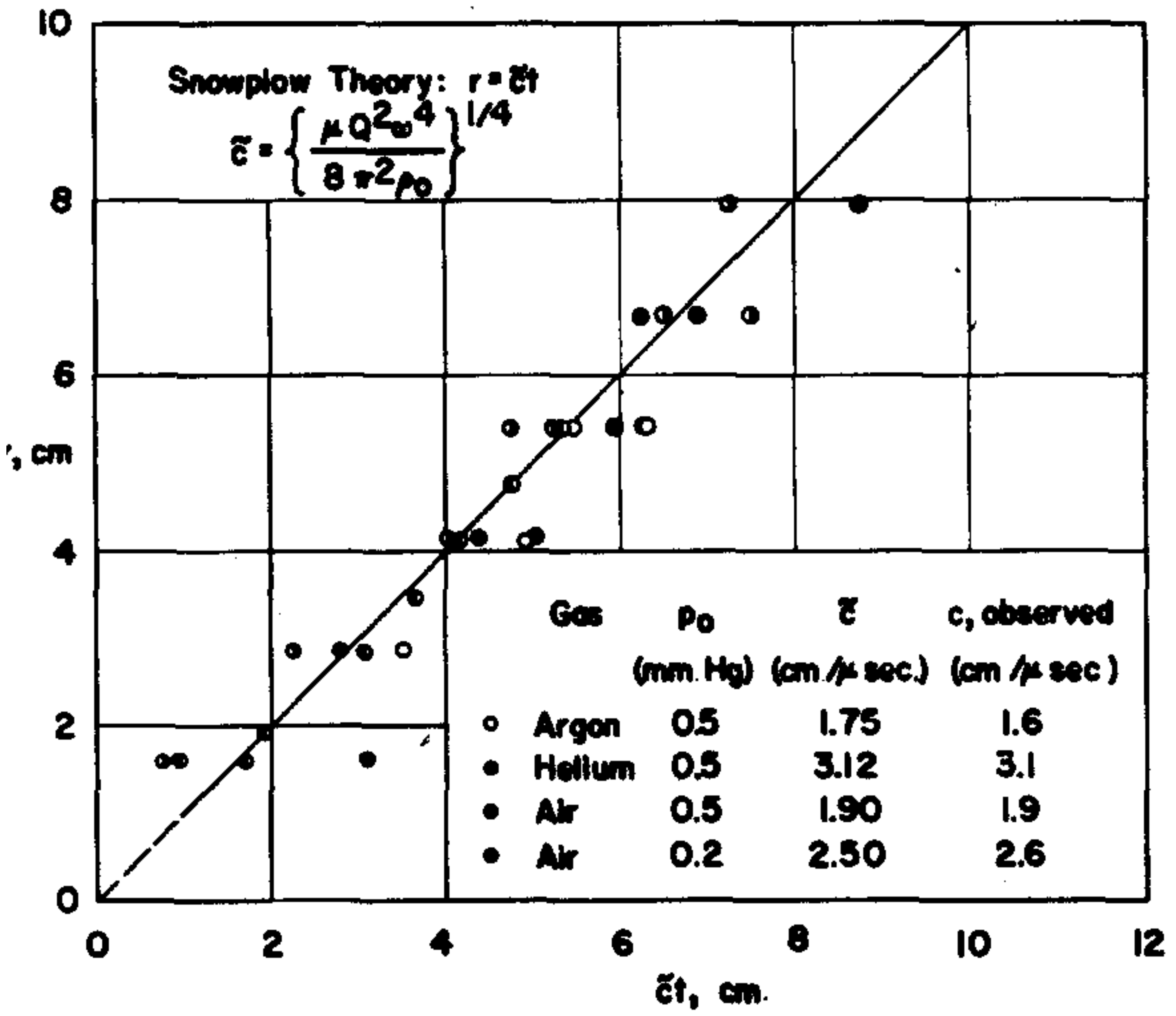
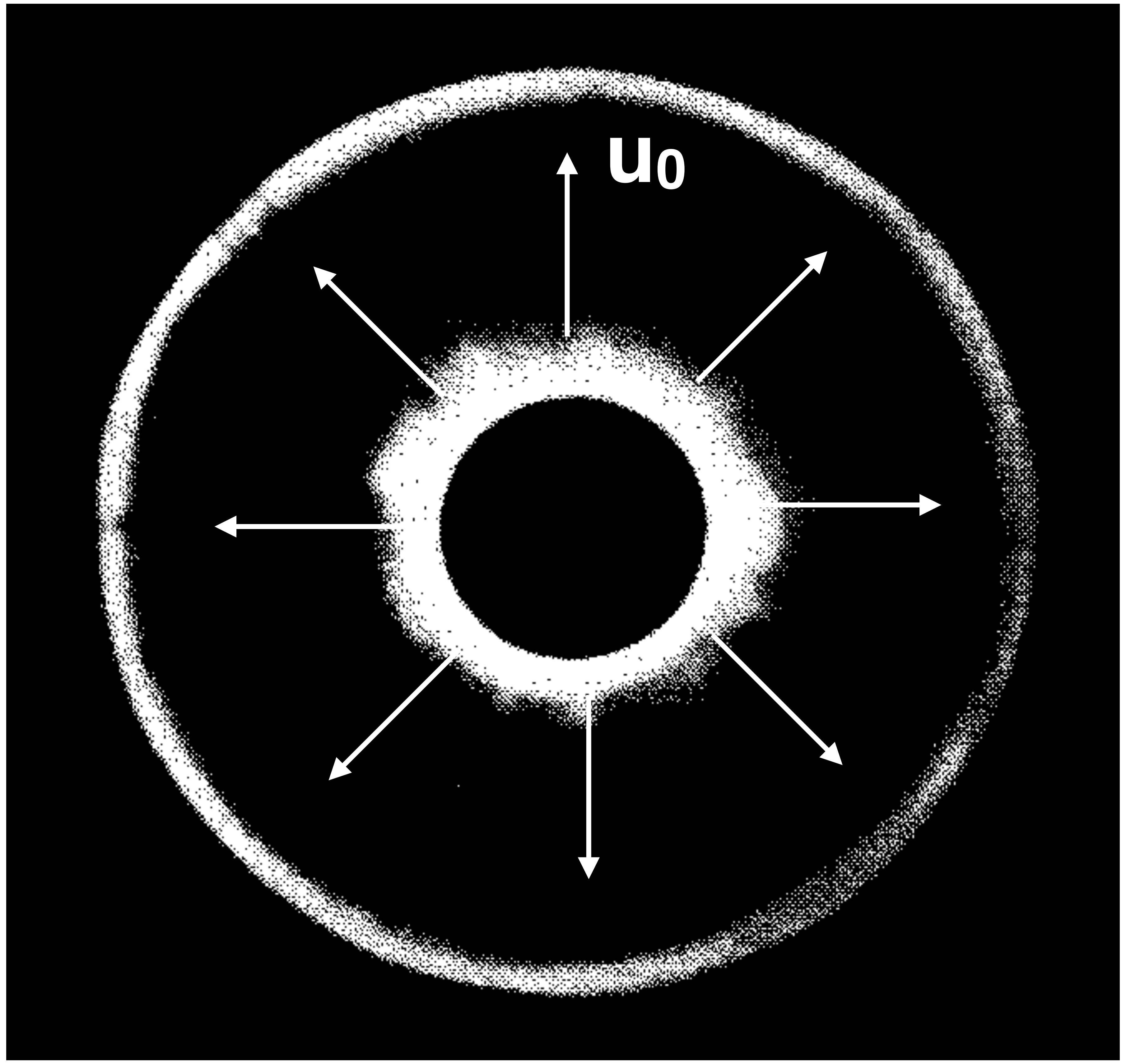


FIG. 2. Summary of pressure-front measurements.

Summary

- Measure the speed, u_0, of an outward moving magnetohydrodynamic shock wave
- Compare speed with nonlinear MHD model

u_0 is shock speed



"Shock and Current Layer Structure in an Electromagnetic Shock Tube,"
George C. Vlases, Phys Fluids 10, 2351 (1967); https://doi.org/10.1063/1.1762043