Experiments in Magnetic Flux Compression Using Plasma Armatures

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A Cooperative Research Project between
UAH/PRC and NASA/MSFC

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Research Mentor: Dr. Ron J. Litchford, NASA/MSFC

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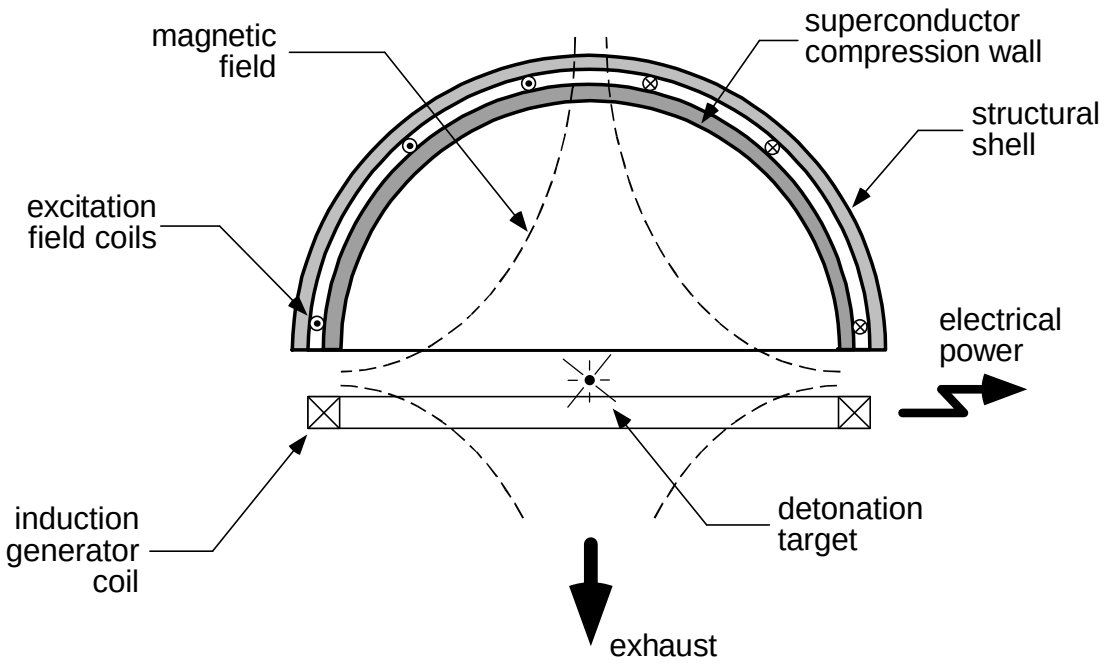
Potential Space Thruster Applications

Magnetic Compression Reaction Chamber



Pulsed Reactor

- Microfusion
- HEDM

Performance Attributes

- improved flux compression
- reduced seed field
- collimated thrust
- power generation

Design Attributes

- smaller
- more compact
- lower weight

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Magnetic Flux Compression with Plasmas

Plasma Jet Characteristics

conductivity	→	relatively low
temperature	→	very high
velocity	→	very high

Major Uncertainties

- achieving sufficiently high electrical conductivity
- suppression of Rayleigh-Taylor surface instabilities

Magnetic Reynolds Number

$$R_m = \frac{B_i}{B_0} = m_0 s u L >> 1 \quad \Rightarrow \quad \text{low magnetic diffusivity} \quad D_m = \frac{1}{s m_0} \sim \frac{1}{R_m}$$

micro fusion detonation	→	$R_m >> 1$
pulsed plasma jet	→	$R_m > 1$
high explosive detonation	→	$R_m > 1$

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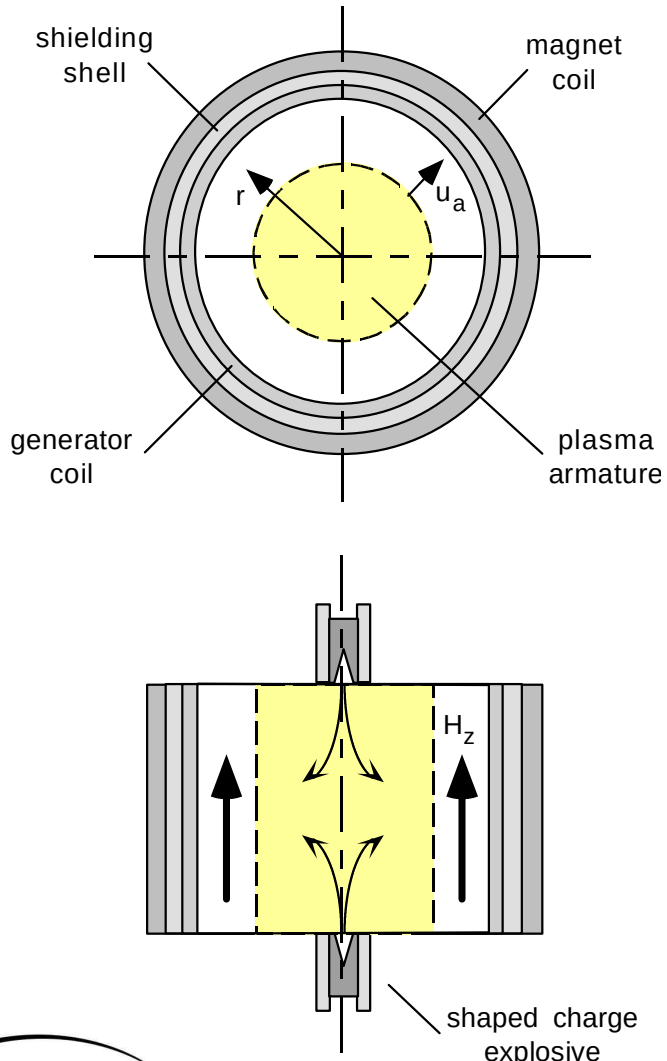
Fundamental Compression Experiments



Research goal is to investigate scientific and technological feasibility using non-nuclear detonations…

Mark 1 Device

Radial-mode, magnetic flux compression reactor

- **Opposing HE charges**
- **Radially expanding plasma armature**
- **Moderate scale technology demonstrator**
- **Low cost expendable unit**

… measurement of plasma electrical conductivity is a critical need

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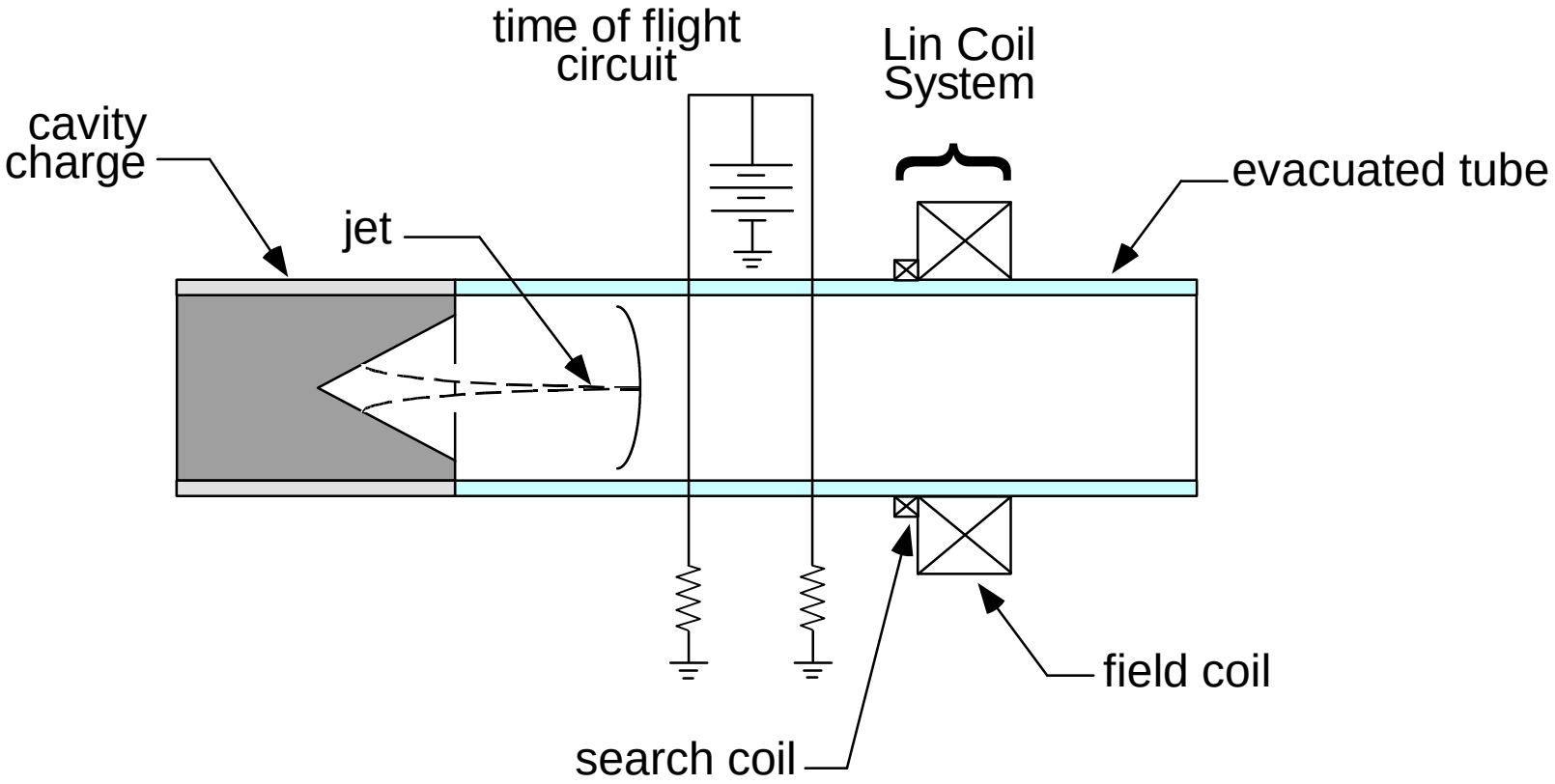
Measurement of Plasma Jet Conductivity



Inductive measurement technique provides a low cost direct measurement of plasma jet electrical conductivity …

Lin, S-C., Resler, E. L., and Kantrowitz, A., "Electrical Conductivity of Highly Ionized Argon Produced by Shock Waves," *J. App. Phys.*, Vol. 26, No. 1, Jan. 1955.

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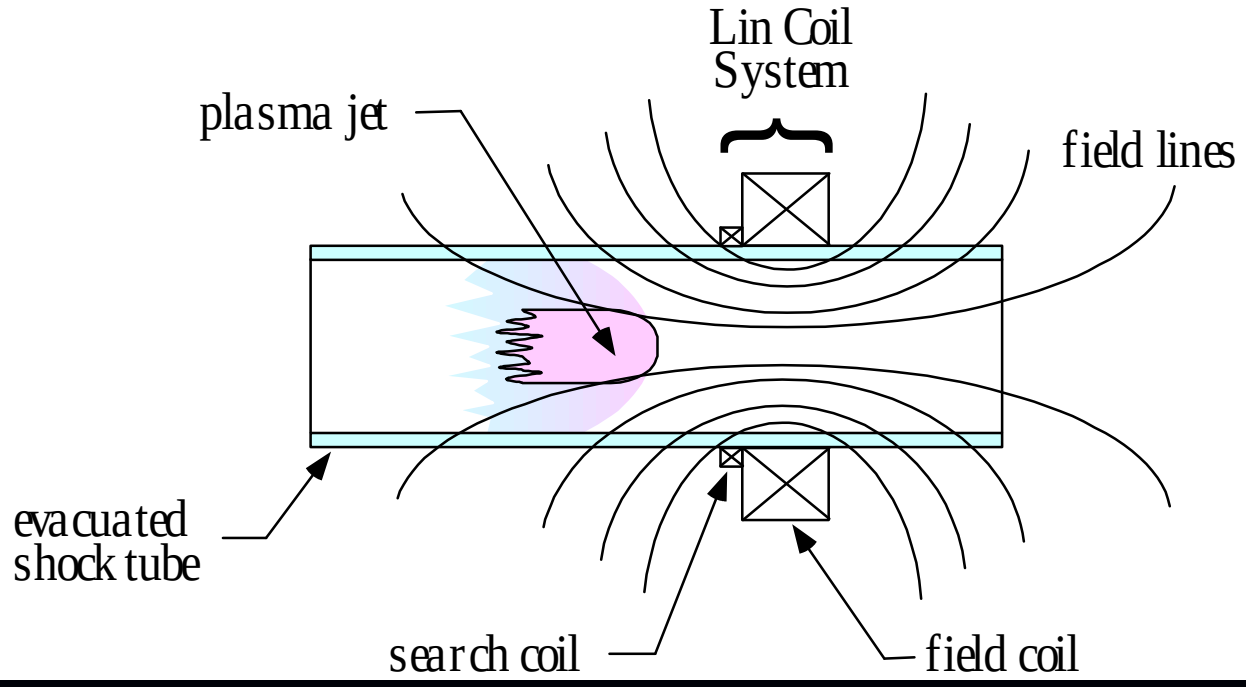
Principle of Inductive Measurement

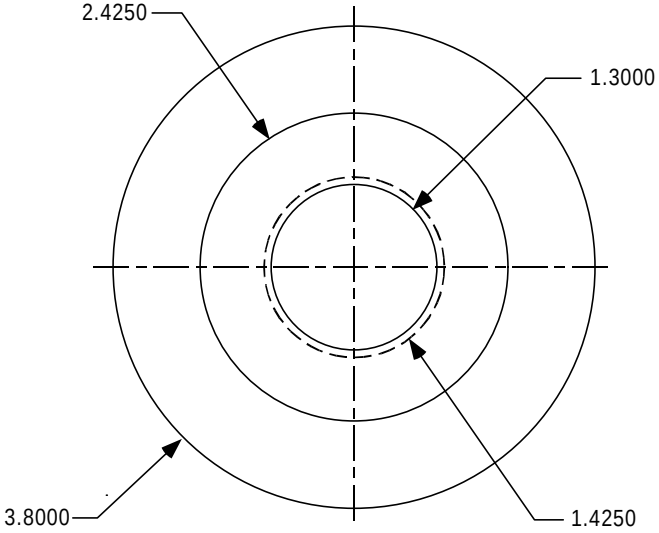


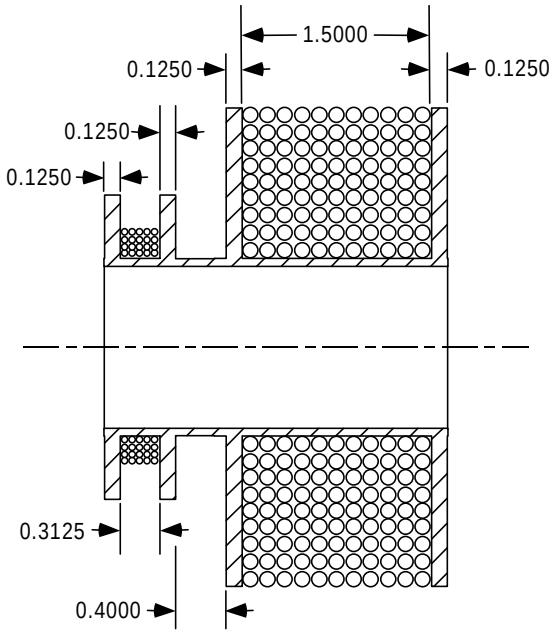
- magnetic field created by field coil
- conductive plasma jet displaces magnetic field lines
- magnetic field lines cut across search coil and induce an emf
- degree of field displacement (emf) is correlated with electrical conductivity
- apparatus calibrated by pre-firing a slug with known conductivity & velocity
- electrical conductivity determined by inversion of Fredholm Eqn. of 1st kind

Lin Coil Design

all measurements in inches

material: nylon





Design Specifications

- **0.5 - 1 Tesla excitation field**
- **1-inch diameter working volume**
- **60 A/ 300 V excitation power limit**

Field Coil
- √ 900-turn coil
- √ No. 18 enameled wire

Search Coil
- √ 50-turn coil
- √ No. 28 enameled wire

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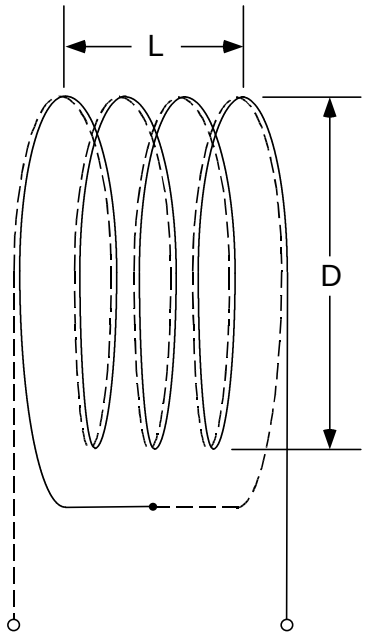
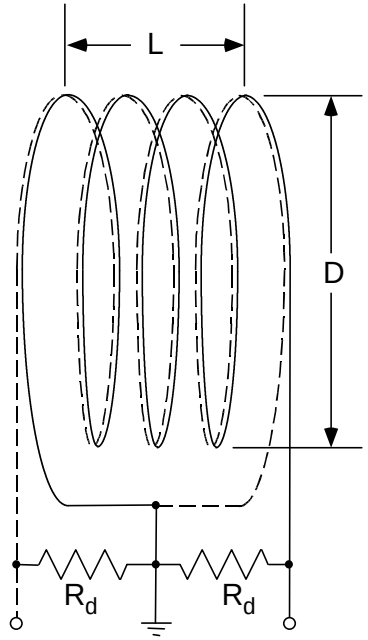
Search Coil Design Considerations

Search Coil Parameters

- 50-turns / No. 28 enamelled wire
- L = 8 mm / D = 5.7 cm
- dual 25-turn coil construction
  - standard option
  - push-pull option



standard configuration



push-pull configuration

Previous experience using inductive conductivity probes with shock layers has shown that a localized electrostatic charge can generate a signal in a standard configuration search coil due to finite capacitance between the coil and the ionized gas inside the tube

Push-Pull Configuration {
- √ cancels capacitive pick-up
- √ R_d is critical damping resistance (≈ 1000 Ω)

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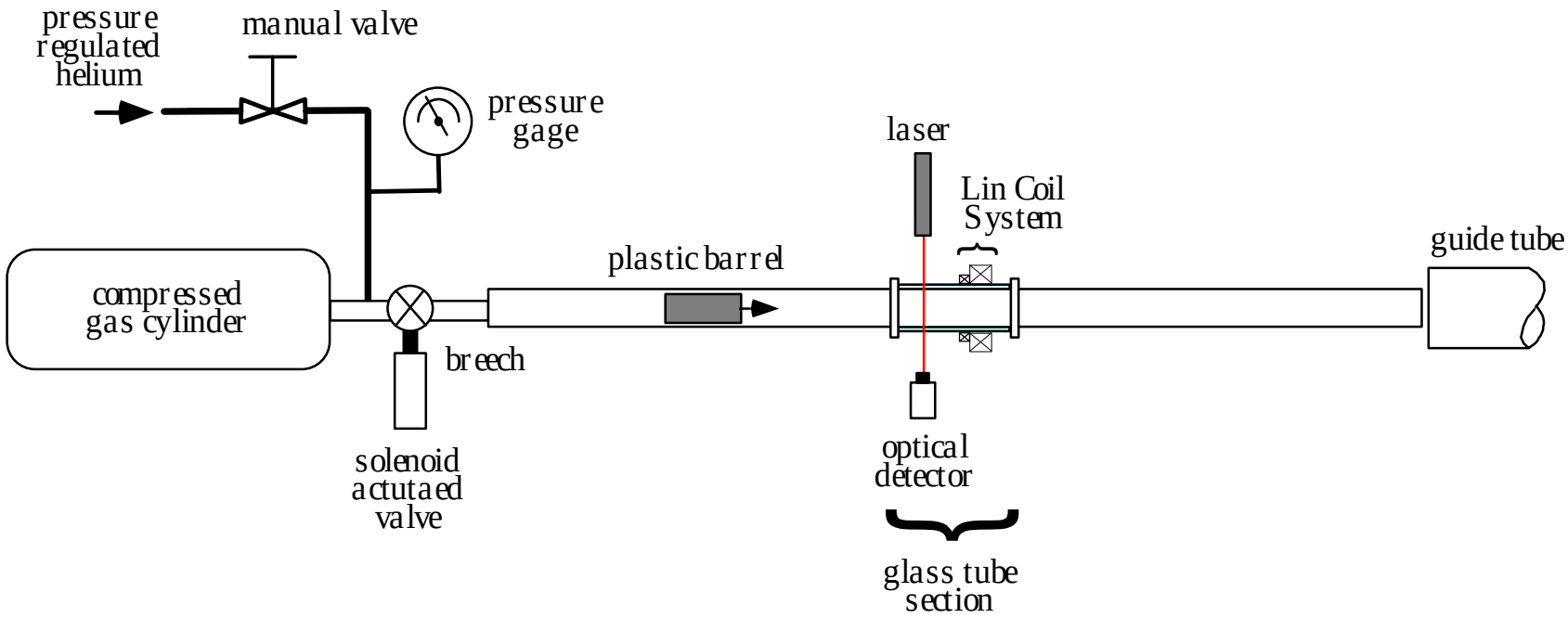
Lin Coil Calibration Apparatus



- light gas gun for slug acceleration (150 psig He)
- 1-inch i.d. plastic barrel with 6-inch long glass test section
- aluminum slug (D = 1-inch / L = 4-inch / ρ = 3(10)$^{-8}$ W-m)
- direct optical measurement of slug velocity
- automated solenoid actuation with high speed data capture

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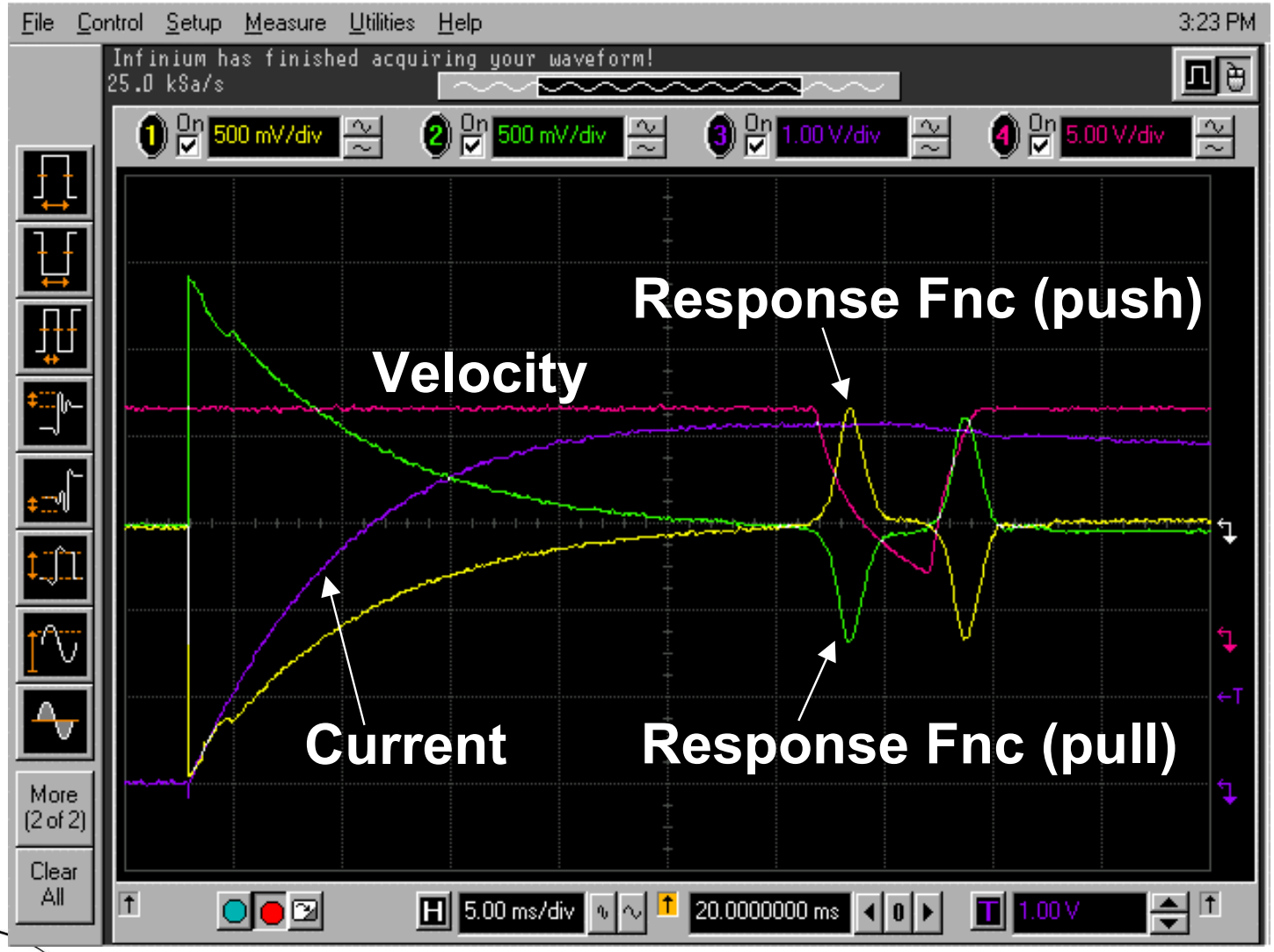
Lin Coil Calibration – Timing Verification



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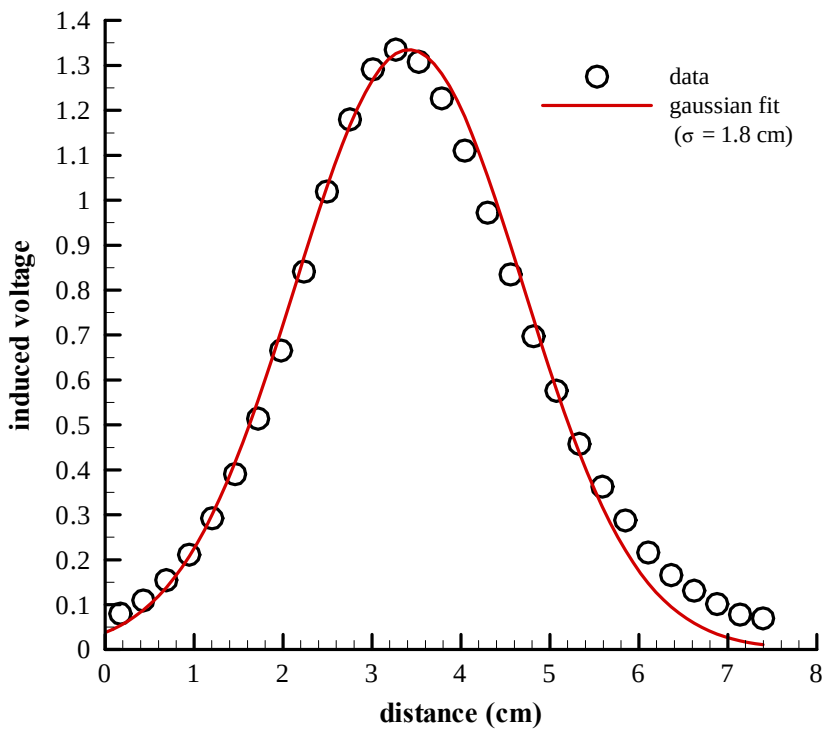
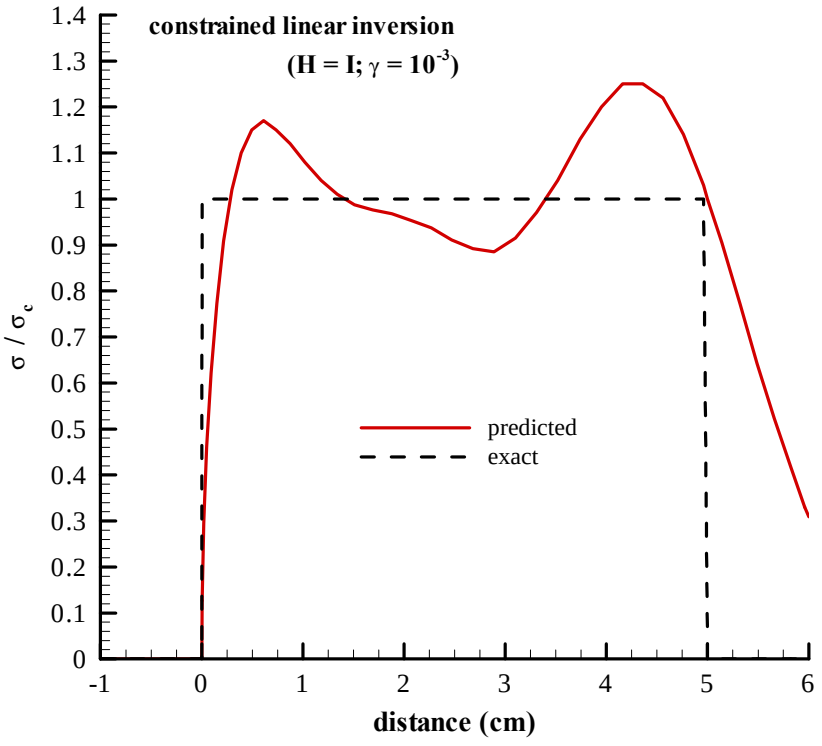
Probe Calibration – Algorithm Verification

Probe Response Function



Algorithm Performance



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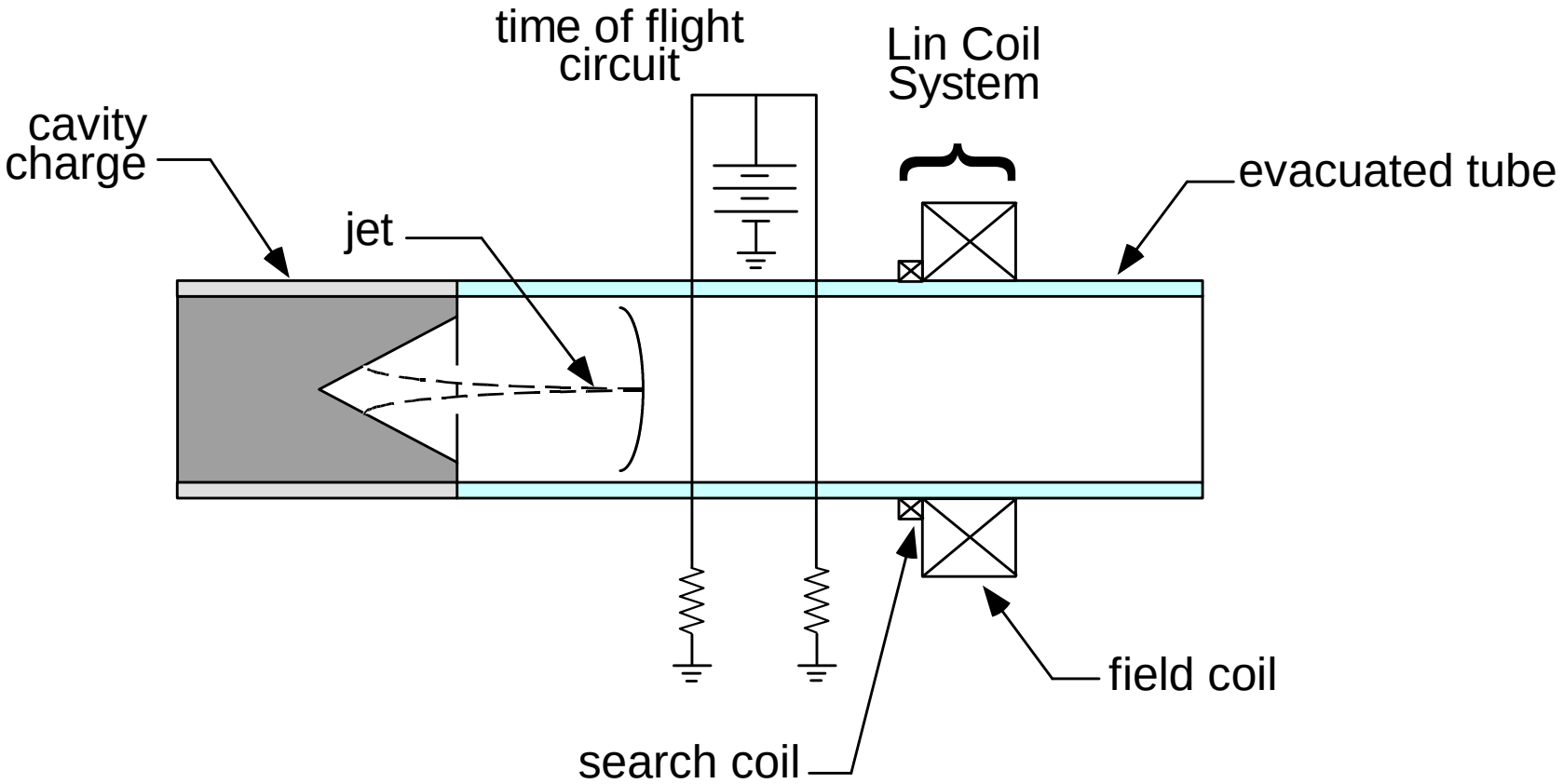
Shape Charge Plasma Jet Conductivity



Plasma Jet Conductivity Measurement

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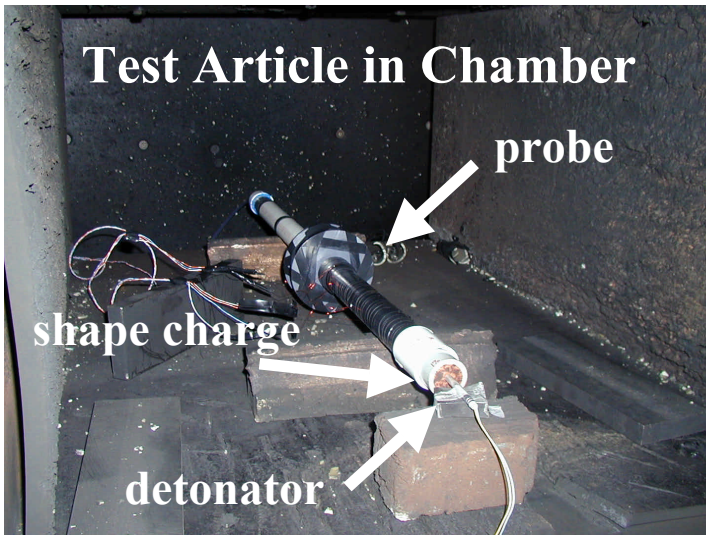
Preliminary HE Testing

- Octol (75% HMX/25% TNT)
- Potassium-Carbonate Seeding
  - 0%, 1%, 2% by mass
- 15 gram shape charges
  - 1.25 inch diameter
  - 44° cone angle



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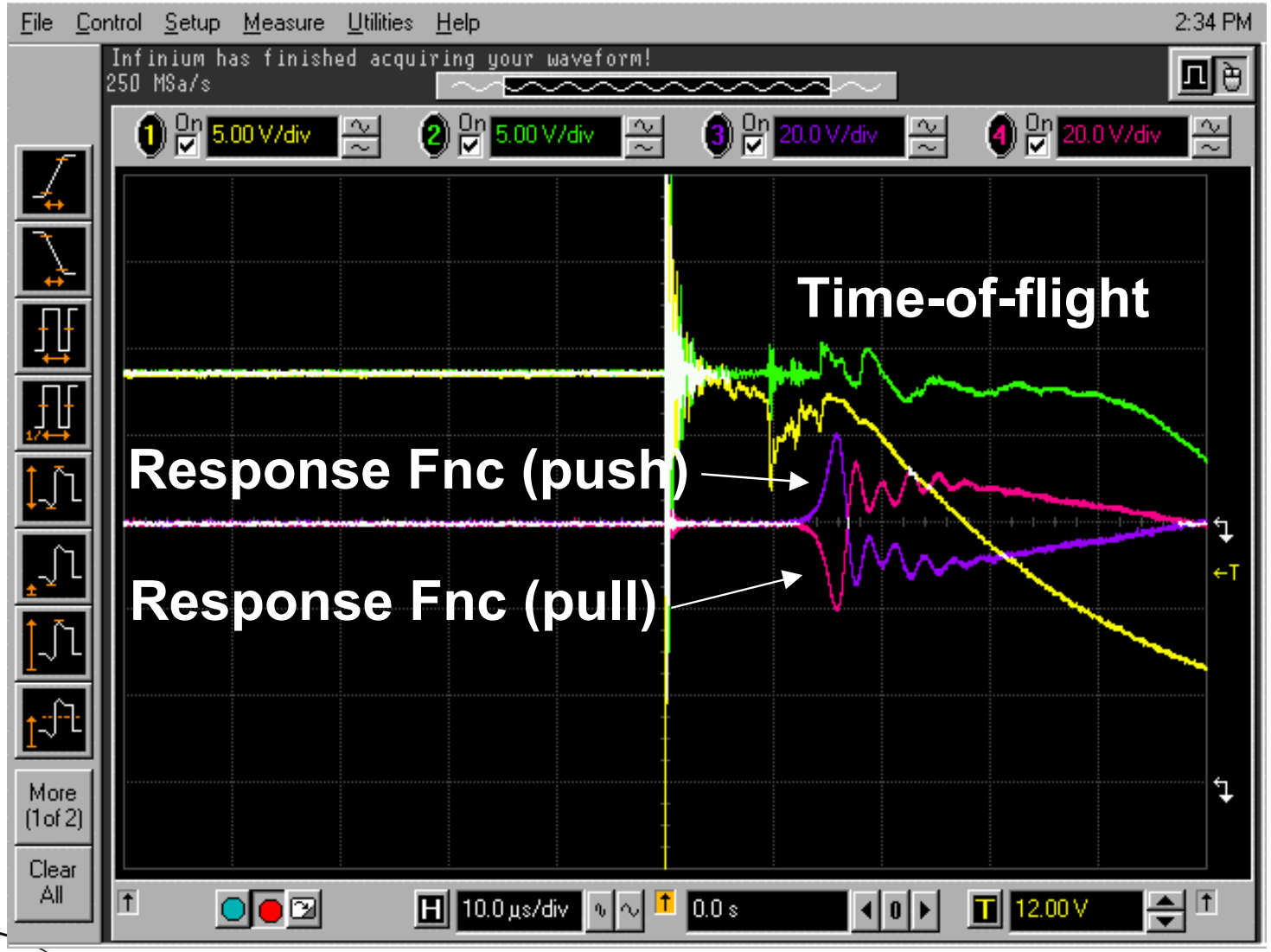
Preliminary Test Results



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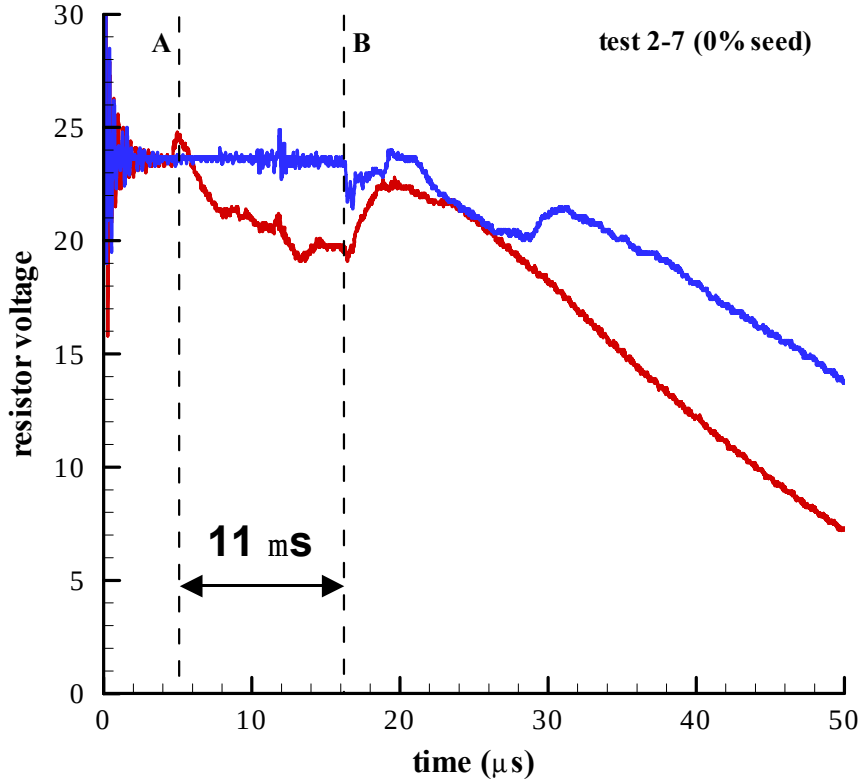
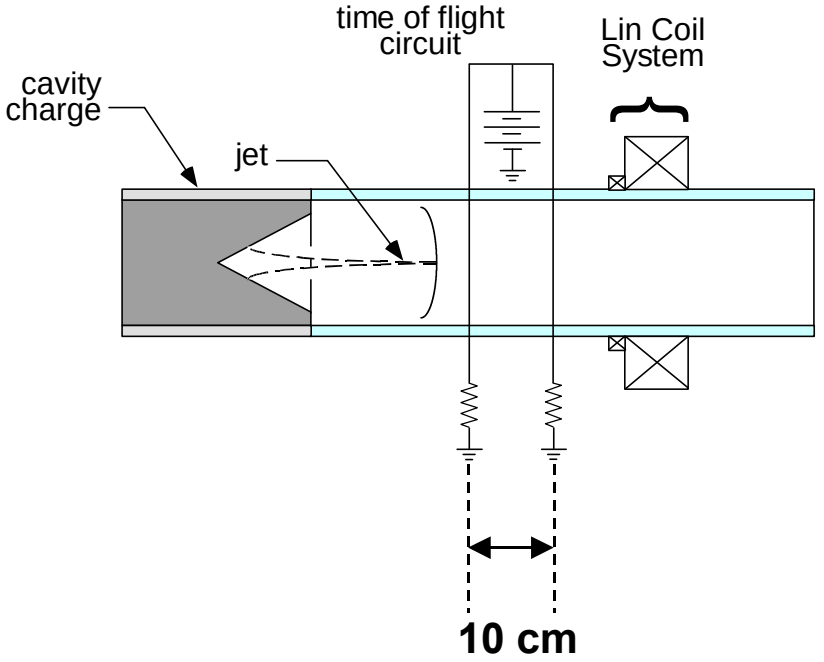
HE Testing – Results

Time-of-Flight Output





Plasma velocity: $u = \frac{dx}{dt} = \frac{10^{-1} m}{11(10)^{-6} \sec} = 9.1\ km/\sec$

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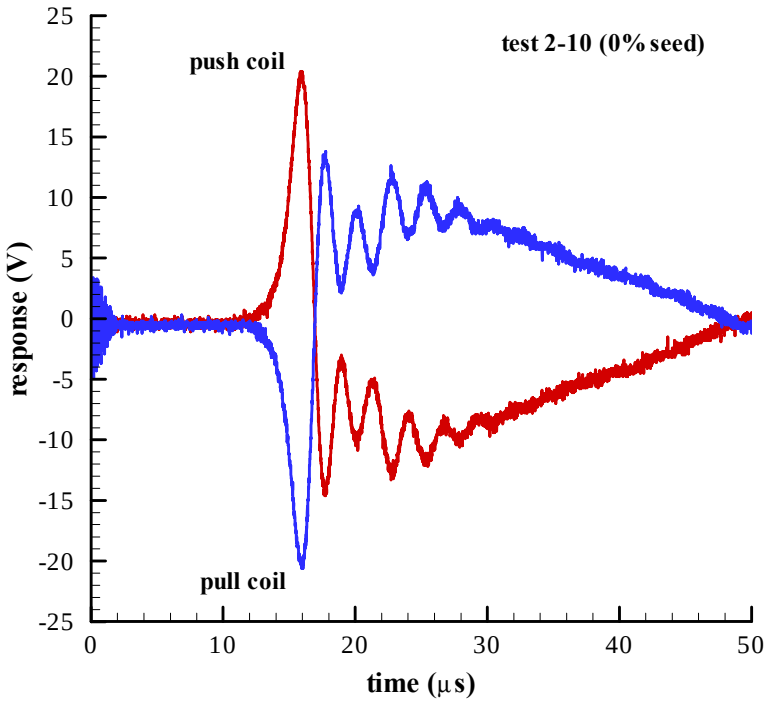
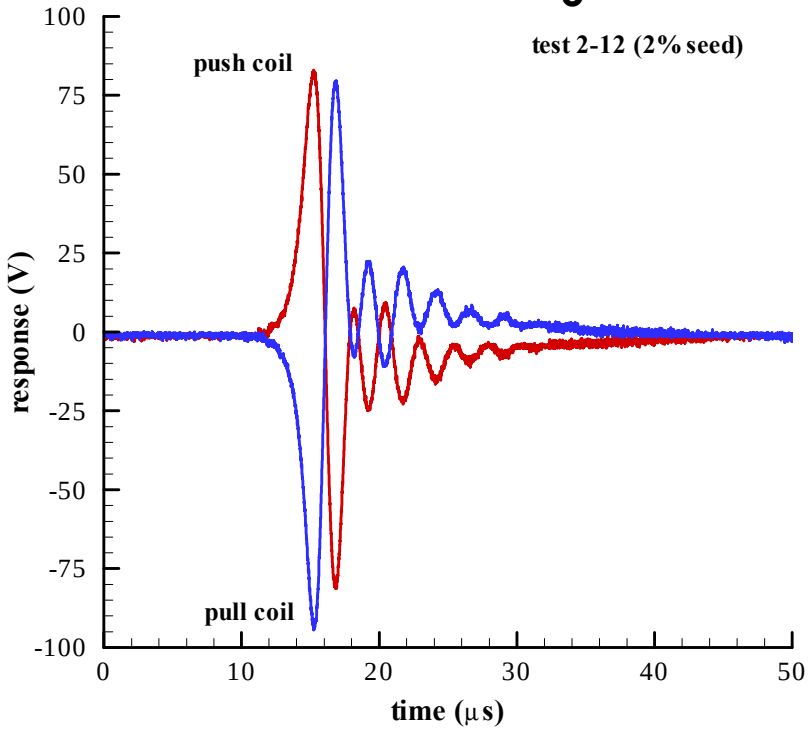
HE Testing – Results

Search Coil Response Function

0% KCO_3



2% KCO_3



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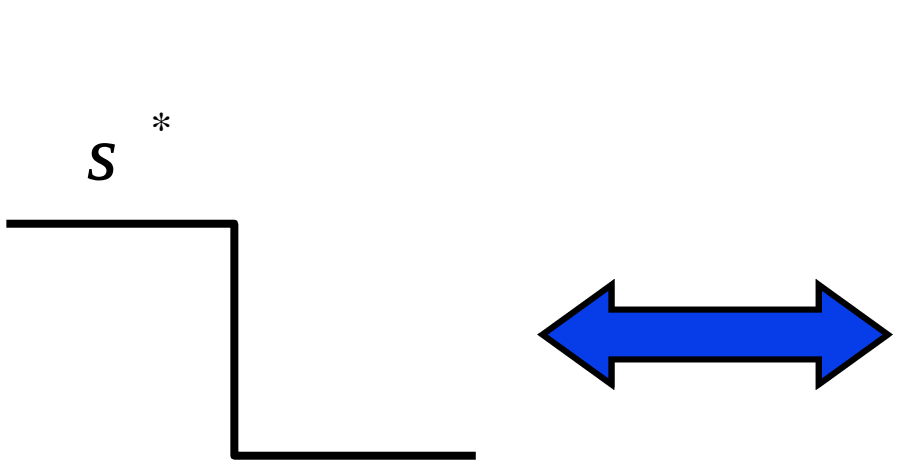
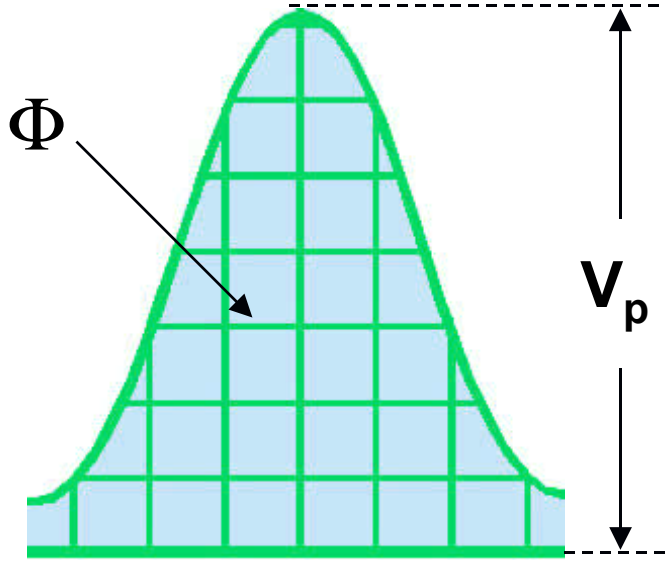
HE Testing – Analysis

Step Function ⟺ **Gaussian Curve**





$$\frac{s^*}{s_c} = \frac{u_c^2 I_c V_p}{U^2 I V_{cp}} \Psi_1 = \frac{u_c^2 I_c \Phi}{U^2 I \Phi_c} \Psi_2$$

For a Gaussian function:

$$\Psi_1 = \Psi_2 = 1$$

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HE Testing – Analysis

Integral Method Calculation: $\frac{s^*}{s_c} = \frac{u_c^2 I_c \Phi}{U^2 I \Phi_c} \Psi_2$

Test	2-4	2-10	2-6	2-12
Seed (%)	0	0	2	2
$\frac{s^*}{s_c} \times 10^{-5}$	5.9	11	58	56
$\frac{s^* u}{s_c u_c} \times 10^{-2}$	2.5	5.1	26	24
$s^*(kS/m)$	1.9	3.6	19	18
$m_0 s^* u(m^{-1})$	22	46	228	210

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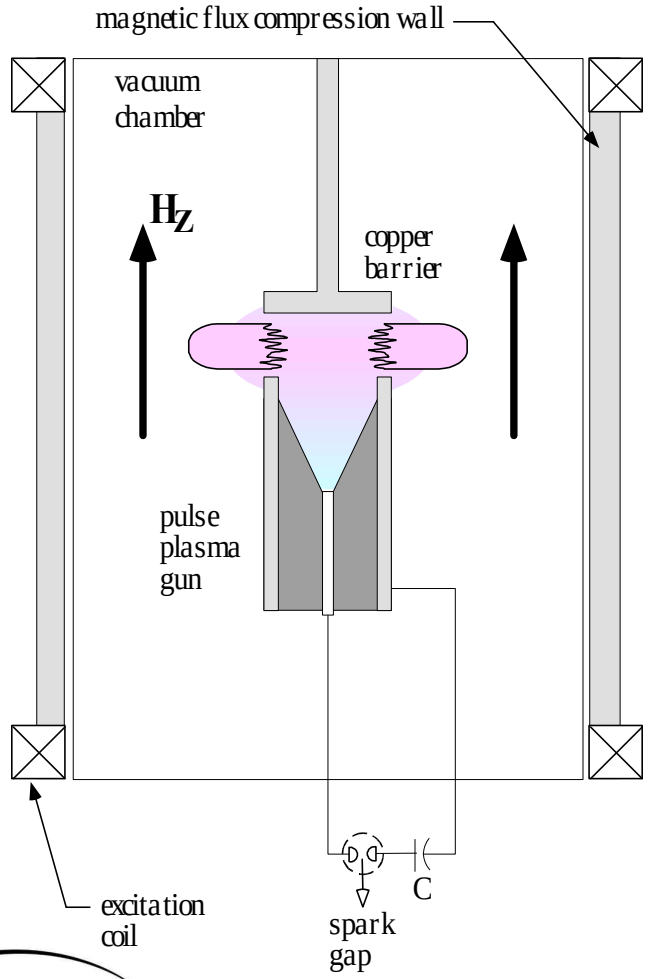
Fundamental Research on Rayleigh Taylor Instabilities



Tapered Pulse Plasma Gun

Plasma Jet Characteristics

$u \sim 10^4$ m/s $T_e \sim 10$ eV

Diagnostics:

- High speed imaging
- Time-resolved interferometry
- Time-resolved spectroscopy
- dB/dt probes

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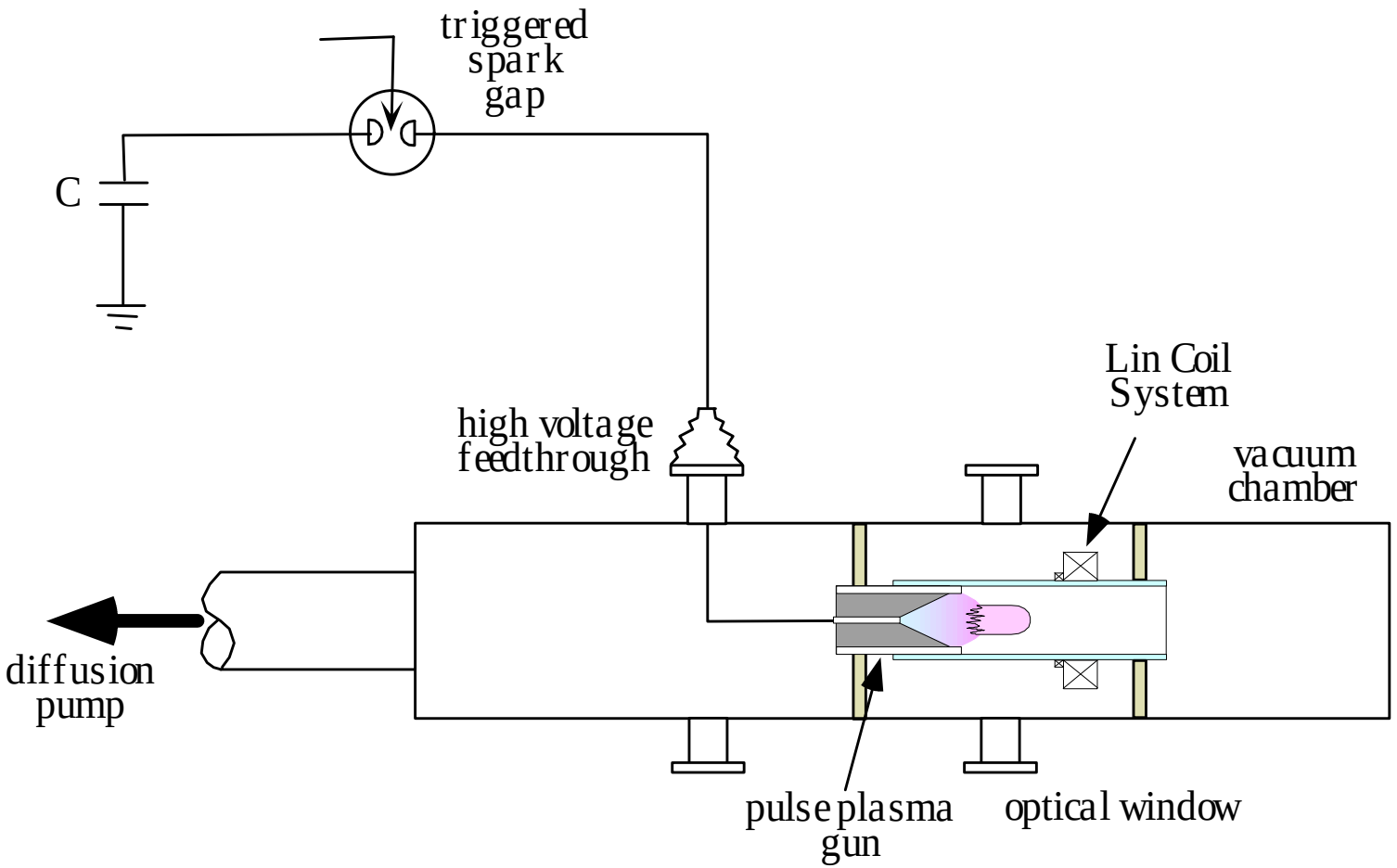
Development of Pulsed Plasma Experiment



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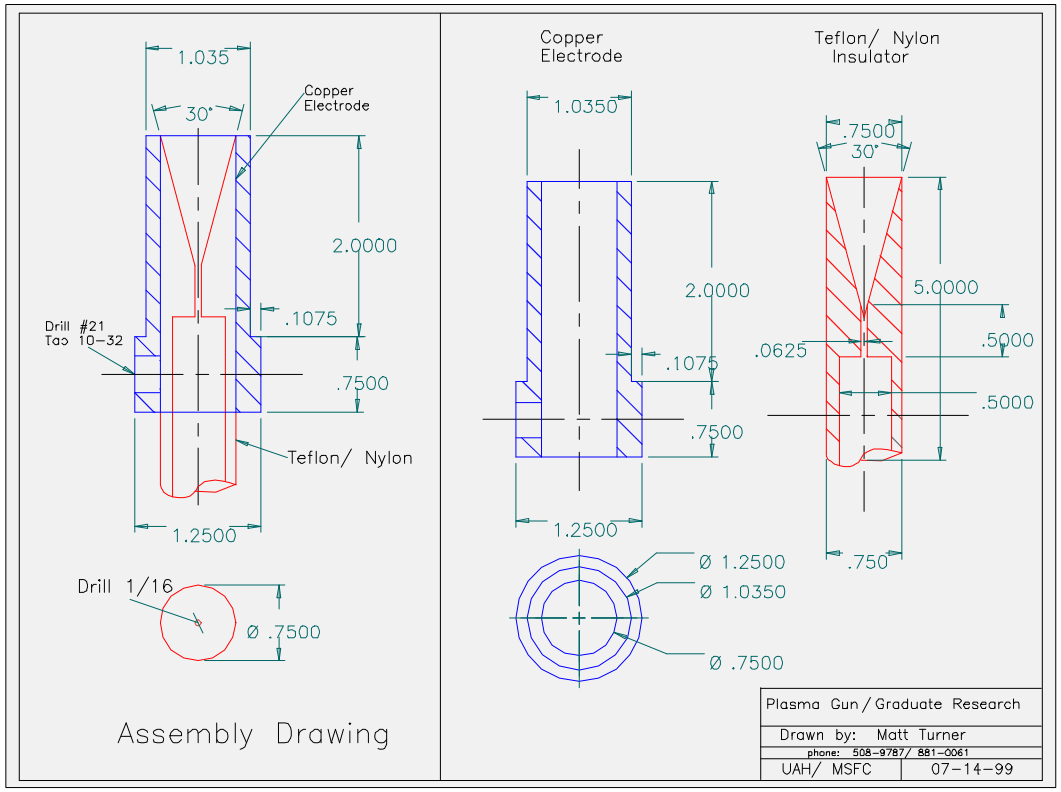
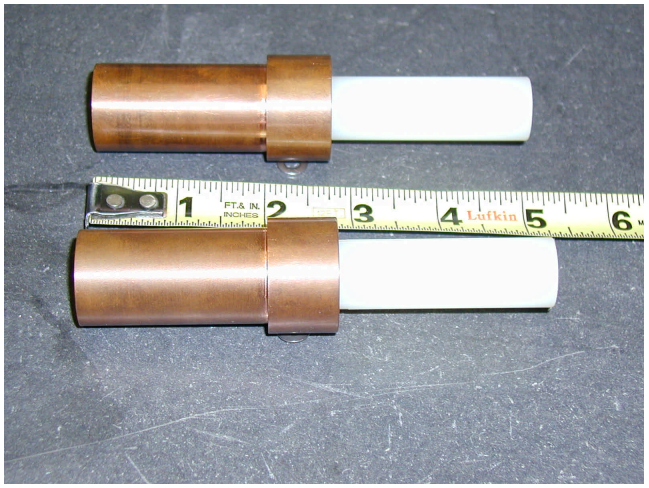
Pulsed Plasma Gun Design





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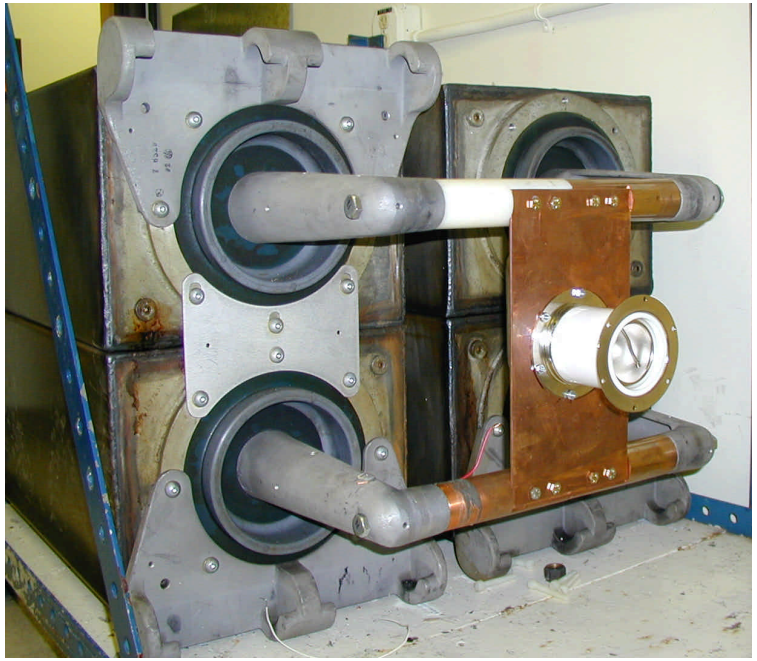
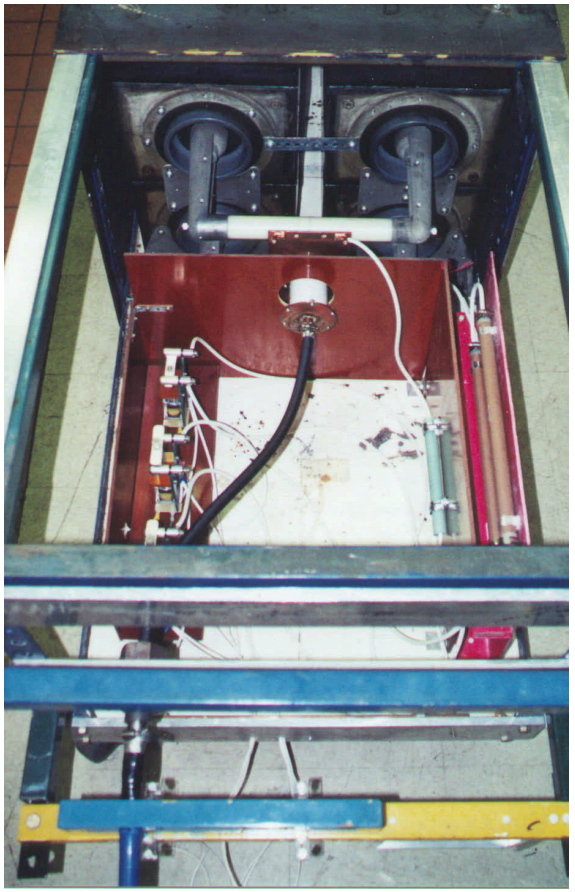
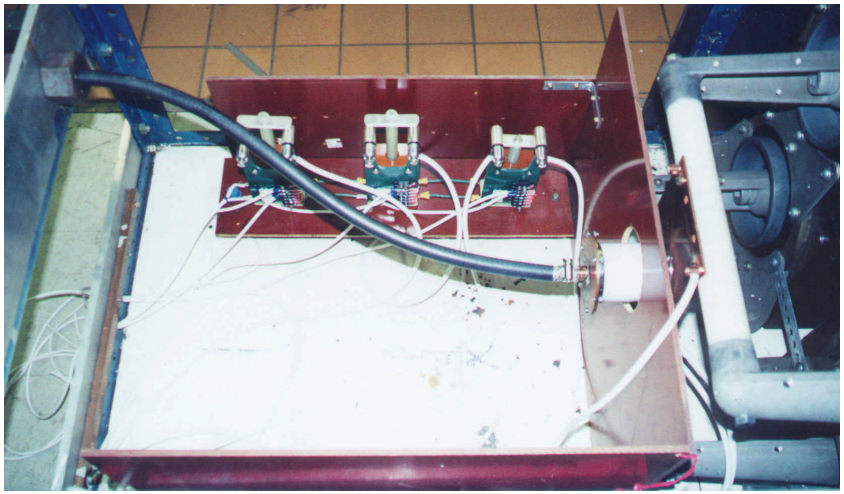
Experimental Set-Up



Design

- four 2-mF capacitors (ONR surplus)
- configurable power bus (1, 2, 3, or 4 capacitors in parallel)





- capacitor bank and discharge circuit mounted on cart for portability

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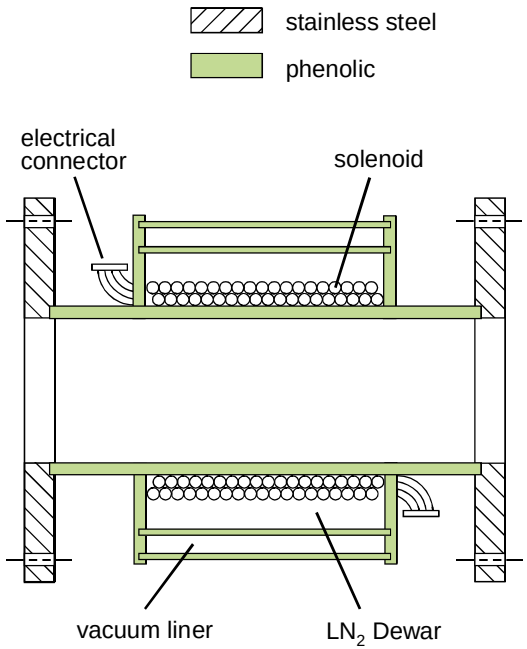
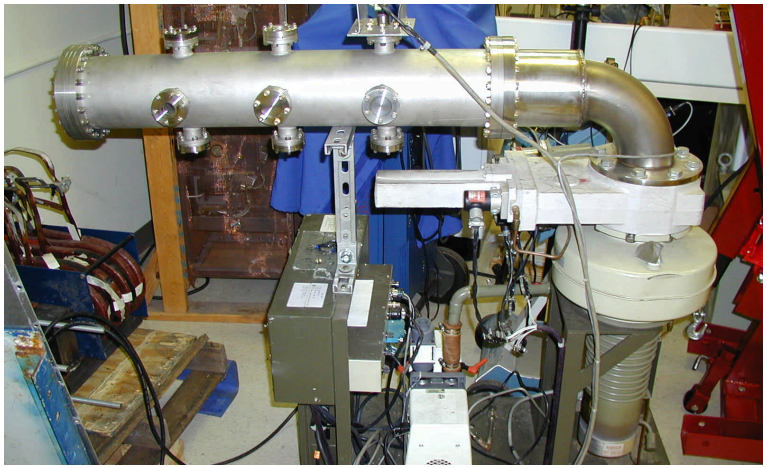
Conclusions

- An electrode-less inductive probe for measuring plasma jet electrical conductivity was designed, calibrated, and tested
- Calibrated with slug of known conductivity
  - Inversion algorithm marginally successful
  - Assumed conductivity distribution with known solutions
- Laboratory experiments using seeded and unseeded shape charge explosives
  - Average jet velocity = 9-10 km/sec
  - Measured conductivities: 4 kS/m (unseeded)
    26 kS/m (2% seed)
- Magnetic Reynolds numbers > 1 (for fractions of a meter scale)
  → Mark 1 device has a good chance of being sucessful
- Inductive probing technique represents a very successful and reliable tool for investigating plasma jet characteristics
- High explosive plasma sources capable of producing high Re_m

Future Plans

1. Pulsed plasma gun / discharge circuit completed
   - tapered plasma gun designed, fabricated, and tested
   - high voltage discharge circuit operational
   - vacuum chamber, pump, feedthroughs assembled
   - high-purity aluminum magnet on its way
   - *testing to begin very soon*
2. Mark 1 Device, radial-mode magnetic flux compression reactor using high explosive shaped charges





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