Holographic Interferometry on the ZaP Flow Z-Pinch Experiment


Aerospace & Energetics Research Program
University of Washington
Abstract

The ZaP Flow Z-Pinch Experiment investigates the effects of sheared axial flow on the m=0 sausage and m=1 kink instabilities. Holographic interferometry is used to measure the behavior of these density perturbations in a sheared-flow Z-pinch plasma. Chord-integrated phase information is recorded during a plasma pulse using a pulsed ruby laser and holographic techniques. Deconvolution of the chord-integrated phase information is used to determine the radial electron density profile and to estimate the radial temperature profile. The experimental methods and results of a density and temperature time survey will be presented, along with their correlation to the stability of the sheared-flow Z-pinch.
Z-pinches are susceptible to two types of instabilities:
- sausage instability \( (m=0) \)
- kink instability \( (m=1) \)

Either mode can disrupt the current through the plasma column, causing the column to become unstable and break.
ZaP Flow Z-Pinch Formation

1) Gas is puffed between electrodes.

2) Gas is ionized, forming plasma. Plasma is pushed along electrodes by the JxB force.

3) Plasma reaches end of inner electrode and begins to form Z-pinch.

4) Stable sheared-flow Z-pinch is formed.

Univ. of Washington
Photos and magnetic field data show Z-pinch stability for ~10-20 µs.

The ZaP flow Z-pinch is stable for 700x the theoretical instability growth time of ~24 ns\(^1\).

Typical operating parameters:
- Velocity \(\approx 10 \text{ cm/\(\mu\)s}\)
- Temperature \(\approx 100 \text{ eV}\)
- Density \(\approx 10^{17} \text{ cm}^{-3}\)
- Pinch length \(\approx 50 \text{ cm}\)
- Pinch radius \(\approx 1 \text{ cm}\)
- Total current \(\approx 250 \text{ kA}\)

Z-pinch Emission Photos Show Stability and Growing Instability

500-600 nm bandpass filter

Univ. of Washington
ZaP Flow Z-Pinch
Magnetic Mode Data Shows a Period of Reduced Mode Activity

Normalized $m=1$ magnetic mode and plasma current ($I_p$) vs. time.
Electron Density Estimate and Measurements

- Electron density estimate
  - Assuming
    - $I_{Z\text{-pinch}} = 1/2 \ I_{\text{Total}} = 125 \ \text{kA}$
    - Constant current density
    - Total temperature = 150 eV
  - $P(r) = -\frac{1}{4} \mu_0 J^2 r^2$ yields $n_e = 10^{16} - 10^{17} \ \text{cm}^{-3}$

- Interferometry\(^1\)
  - Chord averaged density
    - $n_e = 10^{16} - 10^{17} \ \text{cm}^{-3}$

- Holographic interferometry
  - Radial density profile
    - $n_e = 10^{16} - 10^{17} \ \text{cm}^{-3}$

Holographic Interferometry

- Applications
  - Vibration or deformation of opaque objects
  - Density measurements of sufficiently dense, transparent fluids or plasmas
- Electrons in plasma cause a phase shift in scene beam
- Scene beam and reference beam interfere to form fringe pattern
- Density information recorded in two dimensions
ZaP Flow Z-Pinch Experimental Setup

Acceleration region

Assembly region

Holography Port

Inner Electrode

Outer Electrode

Neutral Gas Injection Plane

Pinch Midplane

Vacuum Vessel

Electrode End Wall

1 meter
Holographic Interferometry
Experimental Methods

- Expose hologram
- Develop and reconstruct hologram
- Measure fringe shift
- Determine chord integrated density profile
- Invert chord integrated density profile to obtain radial density profile
Hologram Exposure

• Pulsed ruby LASER (<50 ns)
• Slavich PFG-01 holographic film
• Double exposure
  • 1st without plasma
  • 2nd with plasma
  • Mirror is tilted slightly between exposures
• Fringe patterns of two exposures interfere to produce holographic interferogram (hologram)
• Double exposure method eliminates effects of imperfect optics and path length differences

---

Univ. of Washington
Hologram Reconstruction

- Hologram is developed using darkroom techniques
- HeNe LASER is used to mimic the original reference beam and reconstruct the fringe pattern
- Fringe pattern is recorded on Polaroid film

Univ. of Washington
ZaP Flow Z-Pinch
Plasma Causes Measurable Fringe Shift in Holograms

No plasma present

Plasma present

Reference wires (1 cm apart)

Pulse 21029011

Z-pincha flow direction
Chord Integrated Density Determination

- The fringe shift can be used to find the chord integrated electron number density using the relation

\[ f = \frac{\Delta \phi}{2\pi} = \frac{1}{2 \lambda n_c} \int n_e \, dl \]

- Which simplifies to

\[ N_e = \int n_e \, dl = 3.212 \times 10^{17} \, f \, [\text{cm}^{-2}] \]

\[ f = \text{fringe order} \]
\[ \Delta \phi = \text{phase shift} \]
\[ n_e = \text{electron density} \, [\text{cm}^{-3}] \]
\[ n_c = \text{plasma cutoff density} \]
\[ \lambda = \text{ruby LASER wavelength} \]
\[ N_e = \text{chord integrated electron density} \, [\text{cm}^{-2}] \]

---


Univ. of Washington
Chord Integrated Electron Density

Pulse 21029011
50% hydrogen
50% methane
Radial Density Profile Determination: Abel Inversion

- The chord integrated number density is inverted to yield the radial density profile
- The chord integrated number density is given by

\[ N_e(y) = 2 \int_y^\infty \frac{n_e(r) r dr}{(y^2 - r^2)^{1/2}} \]
- Plasma is modeled as radially symmetric cylindrical shells
- The integral can be discretized (at each of 100 pixels across half of the trough)

\[ N_{ei} = 2 \Delta r \sum_{k=i}^{1-1} A_{ki} n_{ek} \]

- The discretized integral can be expressed as a matrix system

\[ N_e = 2 \Delta r A n_e \]
- The system can be inverted to yield a vector containing the number density at each radial location across the plasma

\[ n_e = A^{-1} \left( \frac{1}{2 \Delta r} \right) N_e \]

\(^2\text{C.M. Vest. Holographic Interferometry,1979.}\)
Radial Density Profile Determination: Abel Inversion

- The elements of the matrix $A$ are just the path lengths through half of each cylindrical shell divided by $\Delta r$, the width of each shell.

$$A_{ki} = \left\{ \left( (k+1)^2 - i^2 \right)^{1/2} - (k^2 - i^2)^{1/2} \right\}$$

- This particular shell method assumes a constant number density across each shell, but other models and methods are possible.$^2$

---


Univ. of Washington
Verification of Inversion Method

- The performance of the inversion method was verified using five test profiles.
- Shown here is the hollow profile corresponding to

\[ n_e \propto r^3 \quad \text{for } 0 < r \leq \frac{1}{2} \]

\[ n_e \propto (1-r)^3 \quad \text{for } \frac{1}{2} < r \leq 1 \]
Radial Electron Density Profile

Pulse 21029011
50% hydrogen
50% methane

Univ. of Washington

ZaP Flow Z-Pinch
Electron Density is Most Peaked During Early Quiescent Period

Normalized m=1 mode, plasma current ($I_p$), and holography laser monitor vs. time

Electron number density vs. radius

Univ. of Washington
ZaP Flow Z-Pinch
Density Profile is Broader and Lower Later in Quiescent Period

Normalized m=1 mode, plasma current ($I_p$), and holography laser monitor vs. time

Electron number density vs. radius

Pulse 21029016
50% hydrogen
50% methane

Univ. of Washington
ZaP Flow Z-Pinch
Interferometer shows Chord Integrated Density Evolution

Normalized m=1 mode and plasma current ($I_p$) vs. time

Chord integrated density vs. time at pinch midplane for impact parameters $y=0$ cm and $y=1.5$ cm

$B_m/B_0$

$n_e (10^{17} \text{ cm}^{-2})$

Pulse 20516006

$100\%$ hydrogen
Conclusions

- Density information can be reliably recorded using holographic interferometry
- Chord integrated density profile can be inverted to obtain radial density profile
- Electron density is highest and profile is most peaked during early quiescent period
- Density profile is broader and lower later in quiescent period
- Time evolution of density profile is consistent with interferometer measurements
Reprints

Reprints available at plasma.aa.washington.edu