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# Observation of Ion-Acoustic Solitons in a Pulsed Magnetron Sputtering Discharge

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## Introduction

- Conventional dc magnetron sputtering processes suffer from fundamental problems such as
  - low target utilization
  - target poisoning
  - poor deposition rates for dielectric materials
- Increased deposition rate requires increased target voltage to achieve a higher plasma density
- This leads to a higher ion flux which in turn increases the target thermal load
- Several sputtering systems have been designed to overcome these obstacles
  - pulsing the applied voltage
  - additional ionization rf or microwave power
  - increased magnetic confinement

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## Introduction

- Two principal methods of pulsing have been proposed:
  - asymmetric bipolar pulsing
  - unipolar pulsing
- Unipolar pulsing utilizes a power supply operating at low (or zero) power level most of the time but pulsing to a significantly higher level for a short period each cycle
  - a high energy pulse (3 – 12 J) of length $\approx 50 - 100$ $\mu$s
  - a repetition frequency of 50 pulses per second
- A dense localized plasma
  - electron density $n_e \approx 10^{19}$ m$^{-3}$

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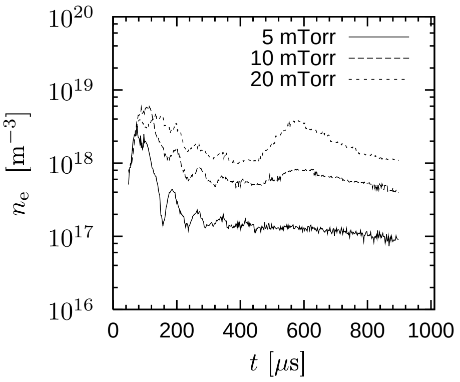
## Electron density



- Electron density $n_e$ versus time from initiation of the pulse 9 cm below a tantalum target
- Pulse length 100 $\mu$s and average power 300 W

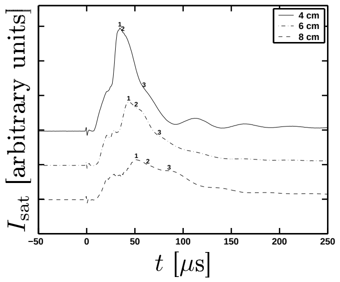
[Gudmundsson et al., 2002]

## Experiental apparatus

- A standard balanced planar magnetron source
  - titanium target of diameter 150 mm
  - stainless steel sputtering chamber of radius $R = 24$ cm and height $L = 75$ cm
- The magnetron cathode is driven by a pulsed power supply
  - 50 pulses per second (20 ms between pulses)
  - The pulse energy was 3 – 6 J and pulse width roughly 70 $\mu$s
- Electron density perturbations were detected using a cylindrical Langmuir probe assuming

$$n_{\rm e} \propto I_{\rm sat}$$

## Electron saturation current



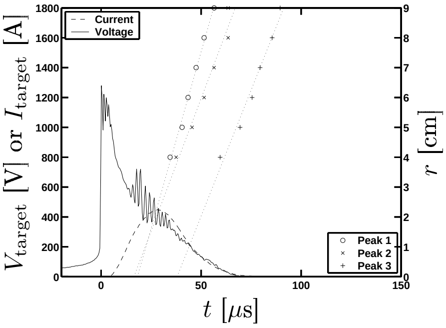
- The electron saturation current, measured by a Langmuir probe, as a function of time from pulse initiation at 4, 6, and 8 cm below the target
- The curves are arbitrarily translated but drawn to scale.
- The argon pressure was 5 mTorr, the target made of titanium, pulse length was $\approx 70\ \mu$ s, and pulse energy 5 J
- Three peaks (labeled 1, 2, and 3) can be identified

## Soliton properties

1. Arbitrary positive (compressive) density perturbations evolve into a superposition of spatially separated solitons
2. The number and amplitude of the solitons is determined by the solution of a time-independent Schrödinger equation
3. The soliton velocity is given by
$$\frac{u}{c_{\rm s}} = [1 + 1/3(\delta n/n_0)]$$
   - $\delta n/n_0$ is the maximum density perturbation
   - $c_s$ is the ion acoustic velocity
4. The spatial width, $D$, of a soliton is proportional to $(\delta n/n_0)^{-1/2}$, which implies $D^2 \delta n/n_0 =$ constant
5. Solitons retain their identity upon collision with other solitons.

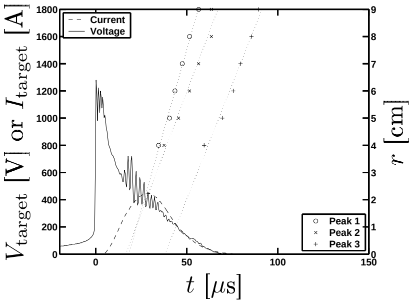
[Hershkowitz and Romesser, 1974]

## Peak trajectory



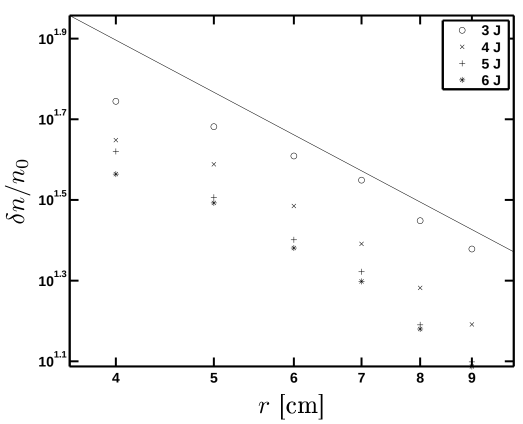
- The left axis shows the applied target voltage and current.
- The right axis shows the position of the density peaks.
- Both are plotted versus the time from pulse initiation
- The argon pressure was 5 mTorr, the target made of titanium, and the pulse energy 5 J

# Peak trajectory



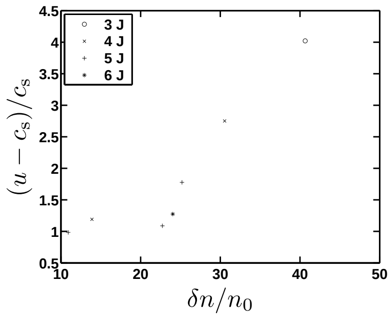
- The trajectories show that the peaks travel with a fixed velocity, which depends on its amplitude, i.e., a large peak travels faster than a small one
- A least squares fit shows that peaks 1 and 2 travel with velocities of $2.4 \times 10^3$ m/s and $1.8 \times 10^3$ m/s respectively and are formed roughly 20 $\mu$s after pulse initiation
- Peak 3 has a velocity of $1.7 \times 10^3$ m/s and is formed roughly 40 $\mu$s after pulse initiation

# Spherical geometry



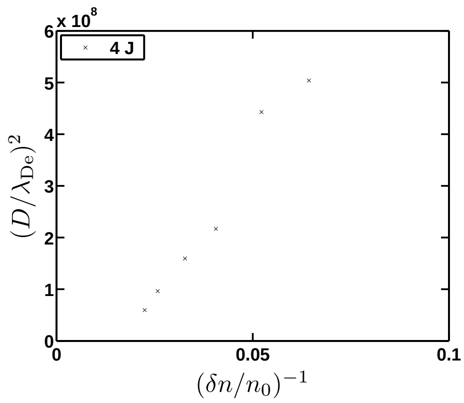
- The maximum density perturbation $\delta n/n_0$ of the leading peak measured at various distances $r$ from the magnetron target for pulse energies of 3 – 6 J
- The solid line is proportional to $r^{-\frac{4}{3}}$

# Soliton velocity



- The velocity of the soliton peaks at 6 cm below the target versus their maximum density perturbation at 6 cm below the target
- For solitons we expect
$$\frac{u}{c_{\text{s}}} = [1 + 1/3(\delta n/n_0)]$$
- The observed relation is linear but the constant of proportionality is close to $\alpha = 0.1$, slightly lower than the $\alpha = 1/3$ to be expected for a one dimensional soliton

# Soliton width



- The square of the normalized spatial width of the soliton peaks versus the inverse maximum density perturbation for pulse energy of 4 J showing
$$D^2 \frac{\delta n}{n_0} = \text{constant}$$

# Summary

- The existence of ion-acoustic solitons in a pulsed magnetron sputtering discharge is confirmed experimentally
- Distinctive features
  - the large amplitude of the solitons (maximum density perturbation $10 < \delta n/n_0 < 100$)
  - the absence of an initial background plasma
- The velocity, width, and amplitude characteristics of the solitons are found to be in agreement with the basic properties of the expanding soliton solution of the Korteweg-de Vries equation in a spherical geometry

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# References

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[Hershkowitz and Romesser, 1974] Hershkowitz, N. and Romesser, T. (1974). Observations of ion-acoustic cylindrical solitons. *Physical Review Letters*, 32:581 – 583.