IGNITION CONDITIONS FOR PERIPHERAL PLASMA IN A GROUNDED CHAMBER CONNECTED TO A DUAL FREQUENCY CAPACITIVE DISCHARGE

M.A. Lieberman

Department of Electrical Engineering and Computer Sciences
University of California
Berkeley, CA 94720

OUR GROUP

Prof. A.J. Lichtenberg — theory and modeling

Prof. J. Verboncoeur — dual/tri frequency PIC simulations

Prof. J.T. Gudmundsson (U. Iceland, visiting) — global modeling and experiments

Dr. Emi Kawamura — PIC simulations of heating

Sangsup Jeong (Samsung, visiting) — experiments and modeling

Sungjin Kim — global modeling and experiments

Alan Wu — PIC simulations of heating and ion energies

Acknowledgements:

Lam Research Corporation
National Science Foundation
UC Discovery/MICRO Programs

Thanks to: Doug Keil, Eric Hudson, and Reza Sadjadi

OUTLINE OF TALK

- Introduction
- Discharge confinement

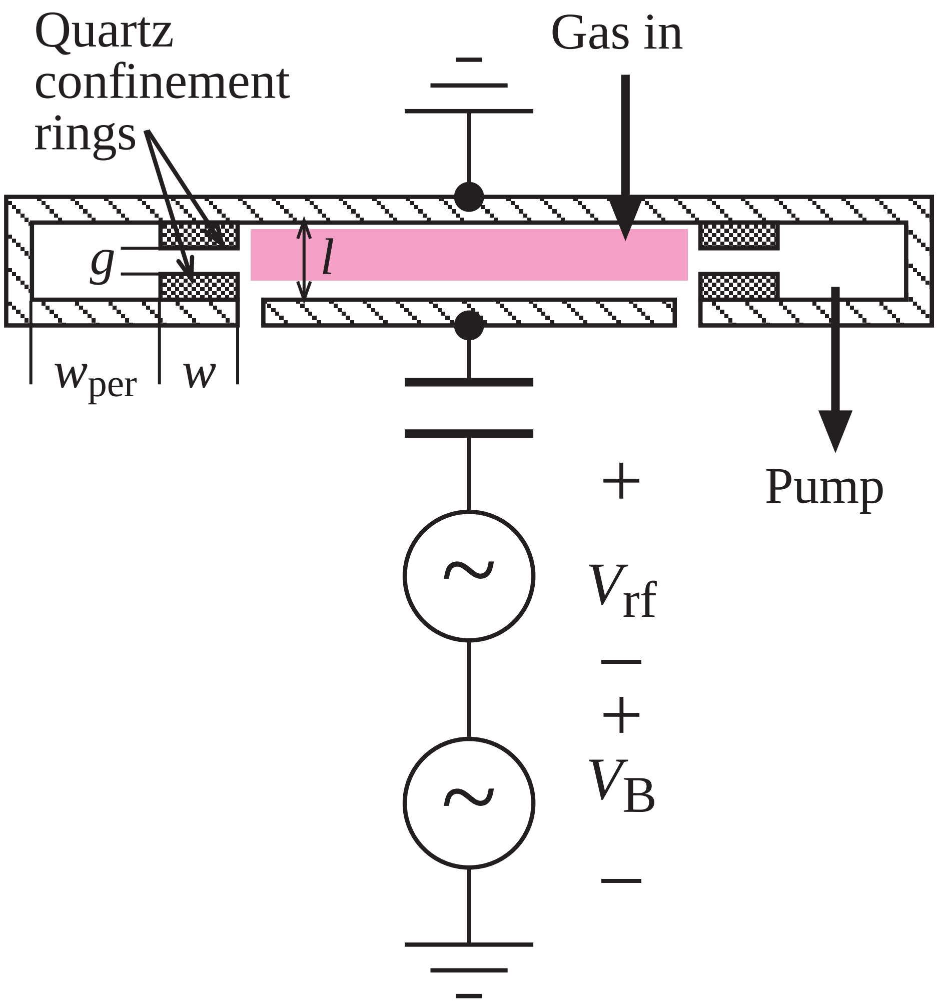
  Plasma diffusion into slot (completed)

  Plasma maintenance in slot and periphery (main topic)

  Berkeley experiment (in progress)

INTRODUCTION

PLASMA CONFINEMENT BY DIELECTRIC RINGS



DUAL FREQUENCY CAPACITIVE DISCHARGES

- $R \sim 15$–30 cm, $l \sim 1$–3 cm
- $p \sim 30$–300 mTorr, $C_4F_8/O_2/Ar$ feedstock
- High frequency $f_{\rm rf} \sim 27.1$–160 MHz, $V_{\rm rf} \sim 100$–1000 V
- Low frequency $f_B \sim 2$–13.56 MHz, $V_B \sim 500$–3000 V
- Absorbed powers $P_{\rm rf},\ P_B \sim 500$–$3000$ W

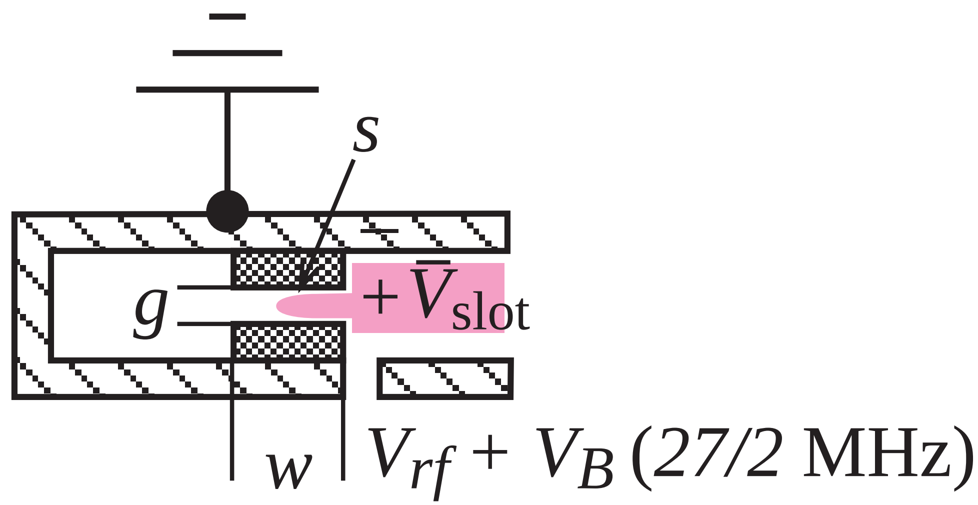
- For independent control of ion flux and energy

$$\frac{\omega_{\rm rf}^2}{\omega_B^2} \gg \frac{V_B}{V_{\rm rf}} \gg 1$$

(M.A. Lieberman, Jisoo Kim, J-P Booth, J-M Rax and M.M. Turner, SEMICON Korea Etching Symposium, p. 23, 2003)

PLASMA TRANSPORT THROUGH SLOT

BASIC DIFFUSION MODEL



- $V_{\rm rf} \Rightarrow$ plasma density n_0 at slot entrance

  $n_{\rm slot}$ decays as plasma diffuses into slot
- $V_B + V_{\rm rf} \Rightarrow$ dc plasma potential $\bar{V}_{\rm slot}$ within slot
- Child law $\Rightarrow$ sheath width s within slot
- As $n_{\rm slot}$ decays, s increases until $s = g/2 \Rightarrow$ plasma "pinch-off"
- Pinch-off length $x_{\rm po} \sim 0.5$–1 cm for 0.5 cm gap g

IMPROVEMENTS TO MODEL

- The sheath and the quartz ring form a capacitive voltage divider for the slot voltage

$\Rightarrow$ reduced sheath voltage and modest increase in pinch-off length

- Low pressure diffusion model in slot for $\lambda_i \gtrsim (T_i/T_e)g$

  $\Rightarrow$ modest increase in pinch-off length

- Sheath width varies with position within the slot

  $\Rightarrow$ slightly reduced pinch-off length

- Finite ionization rate within the slot

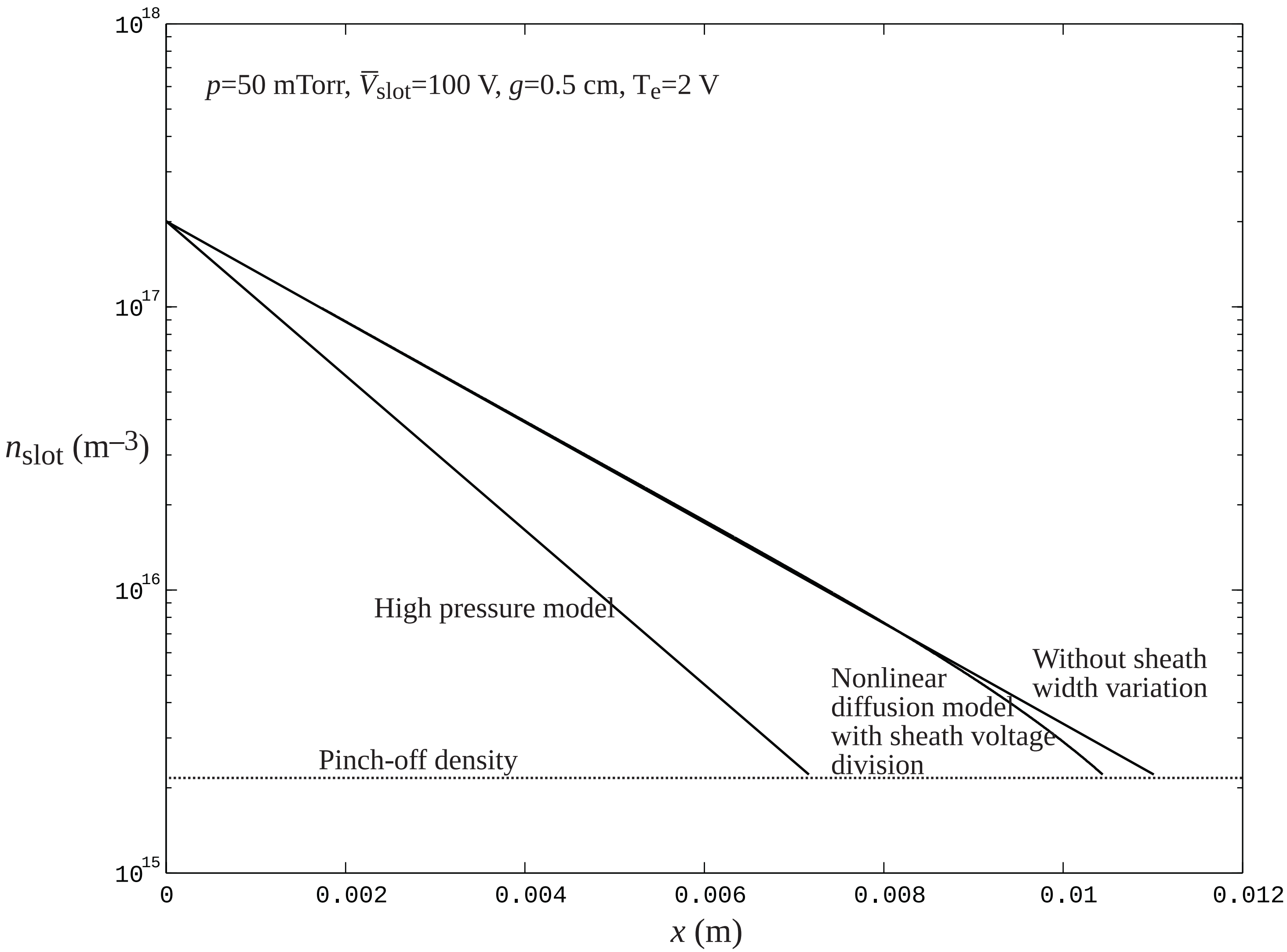
  $\Rightarrow$ modest increase in pinch-off length

- Collisional (not collisionless) Child law sheath in the slot

  $\Rightarrow$ slightly increased pinch-off length

MODEL RESULTS

(collisionless sheath without ionization in slot)



PINCH-OFF LENGTH

- A good estimate of the pinch-off length is

$$x_{\text{po}} \sim \frac{2g}{\pi} \ln\left(0.12\frac{g^2}{\lambda_{\text{D0}}^2}\frac{\text{T}_e^{3/2}}{\bar{V}_{\text{slot}}^{3/2}}\right)$$

where $\lambda_{\text{D0}} = (\epsilon_0 \text{T}_e/en_o)^{1/2}$ = Debye length at slot entrance

- There is a weak pressure dependence at high pressures

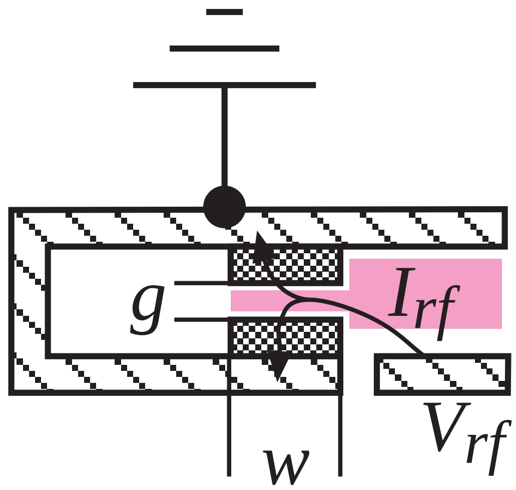
- For typical plasma parameters

$$x_{\text{po}} \sim 2g < \text{slot width } w$$

$\Rightarrow$ plasma does not diffuse through slot into periphery

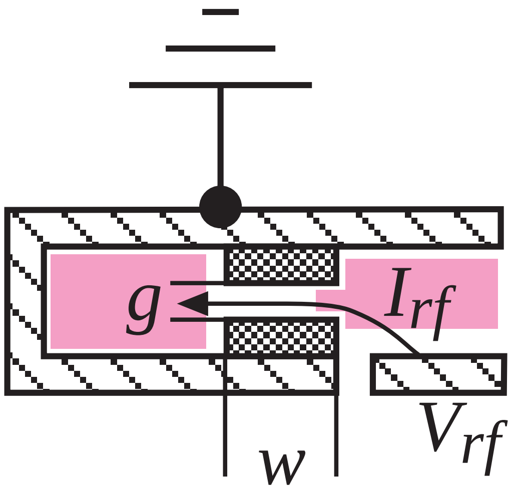
DISCHARGE MAINTENANCE IN SLOT AND PERIPHERY

DISCHARGE IN SLOT



- What are conditions for discharge maintained in slot? ("Maintenance curve")
- "Breakdown" in slot not an issue with main discharge present
- Discharge in slot $\Longrightarrow$ discharge in periphery

DISCHARGE IN PERIPHERY



- For no discharge in slot, what are conditions for discharge maintained in periphery?
- "Breakdown" of periphery (as opposed to maintenance) may be an issue (to be investigated)
- Discharge in periphery $\not\Longrightarrow$ discharge in slot

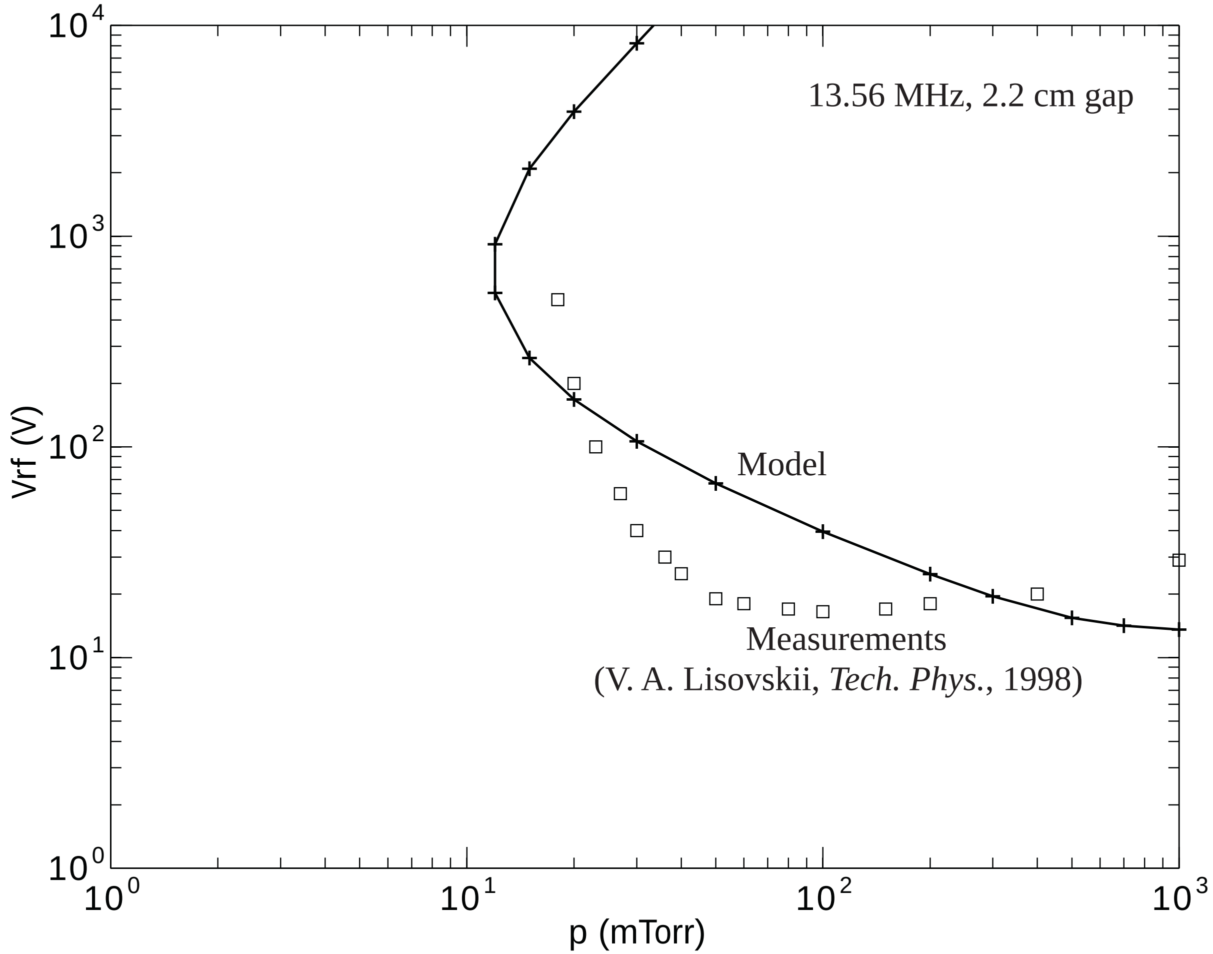
1D MODEL OF DISCHARGE MAINTENANCE

- Basic physics:
  - At low voltages (densities), total width of sheaths approaches gap spacing $\Rightarrow$ bulk plasma becomes too thin
  - Ionization balance or power balance is lost

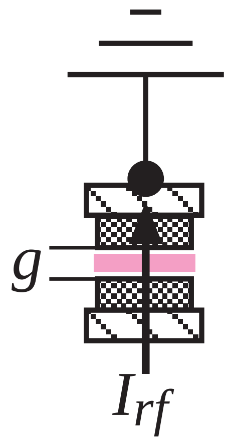
- Global model with additional physics at low rf voltages:
  - Account for a dc/low frequency sheath width in the absence of a high frequency sheath (Godyak/Sternberg, 1990)
  - Account for high frequency voltage drops across the dc/low frequency sheaths and the bulk plasma
  - Account for transition from ambipolar to free diffusion as bulk plasma becomes thin (Allis/Rose 1954)

BENCHMARK 1D MODEL AGAINST MEASUREMENTS

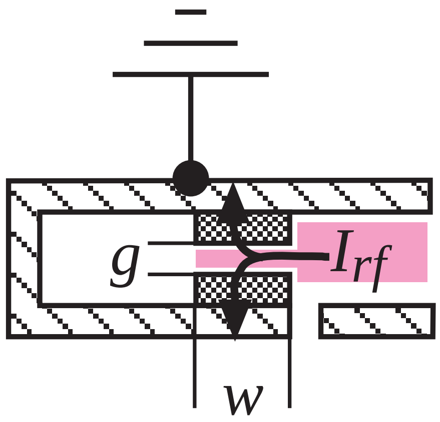
- Conventional capacitive discharge (argon)



2D RF CURRENT FLOWS IN SLOT



Conventional
rf discharge



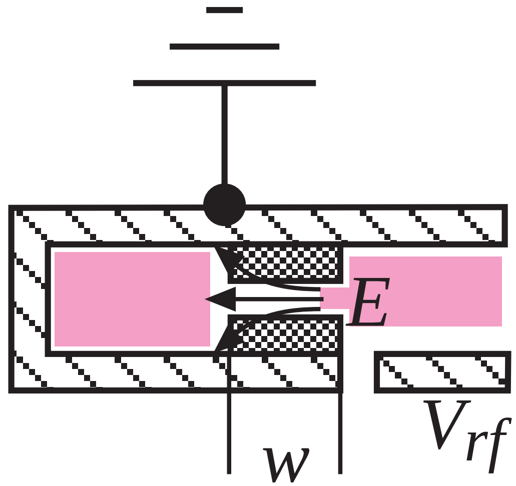
Slot discharge

- Standard 1D global model has rf current transverse to plates
- Symmetric excitation of discharge in slot has 2D currents

  $\Rightarrow$ enhanced ohmic heating, incorporated into model
- When periphery ignites, current drawn through slot increases

  $\Rightarrow$ incorporated into model

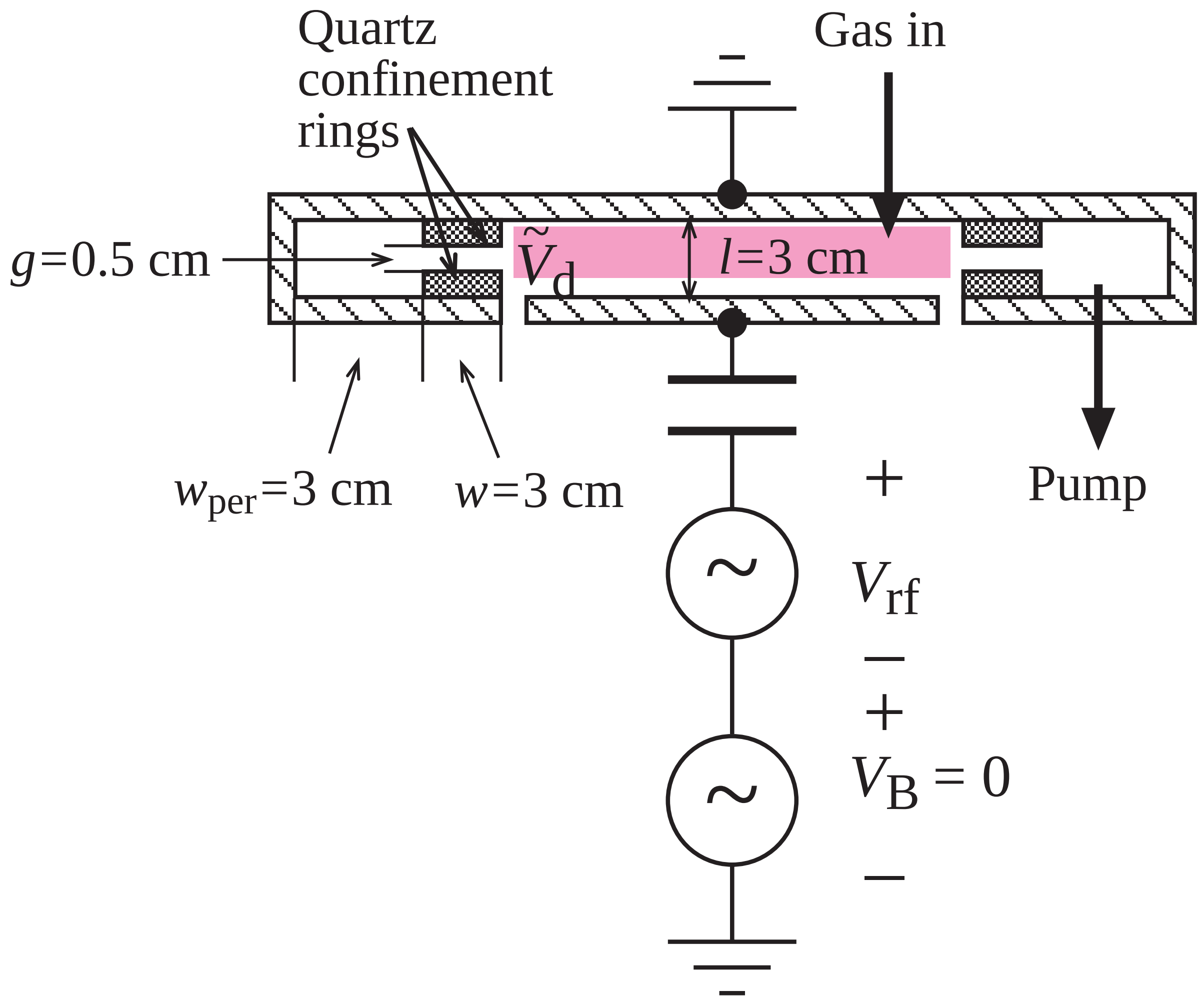
2D CAPACITIVE COUPLING ACROSS SLOT



- Solve for decay of electric field E in dielectric region
- Decay depends on pinch-off length

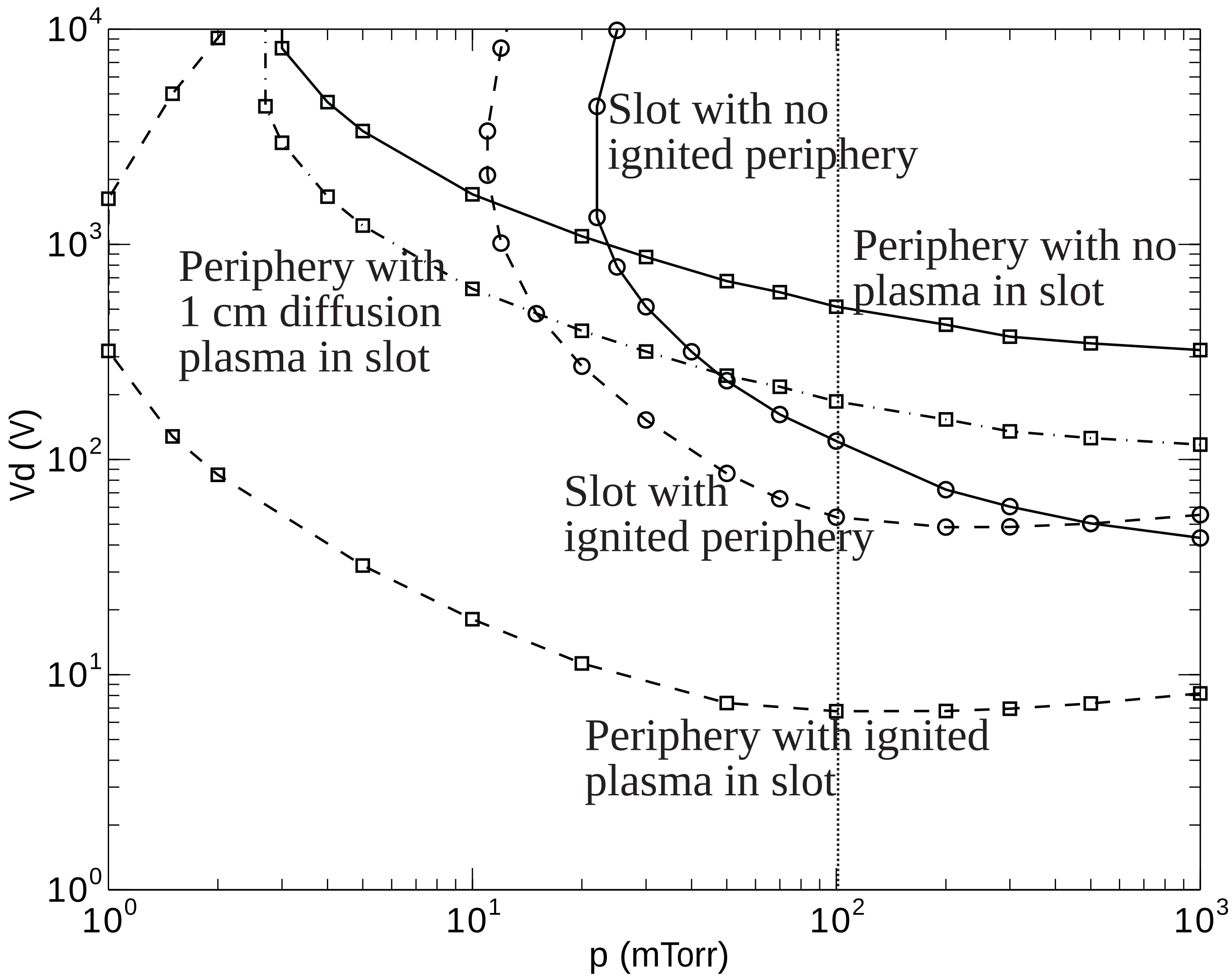
$\Rightarrow$ incorporated into model

NOMINAL PARAMETERS



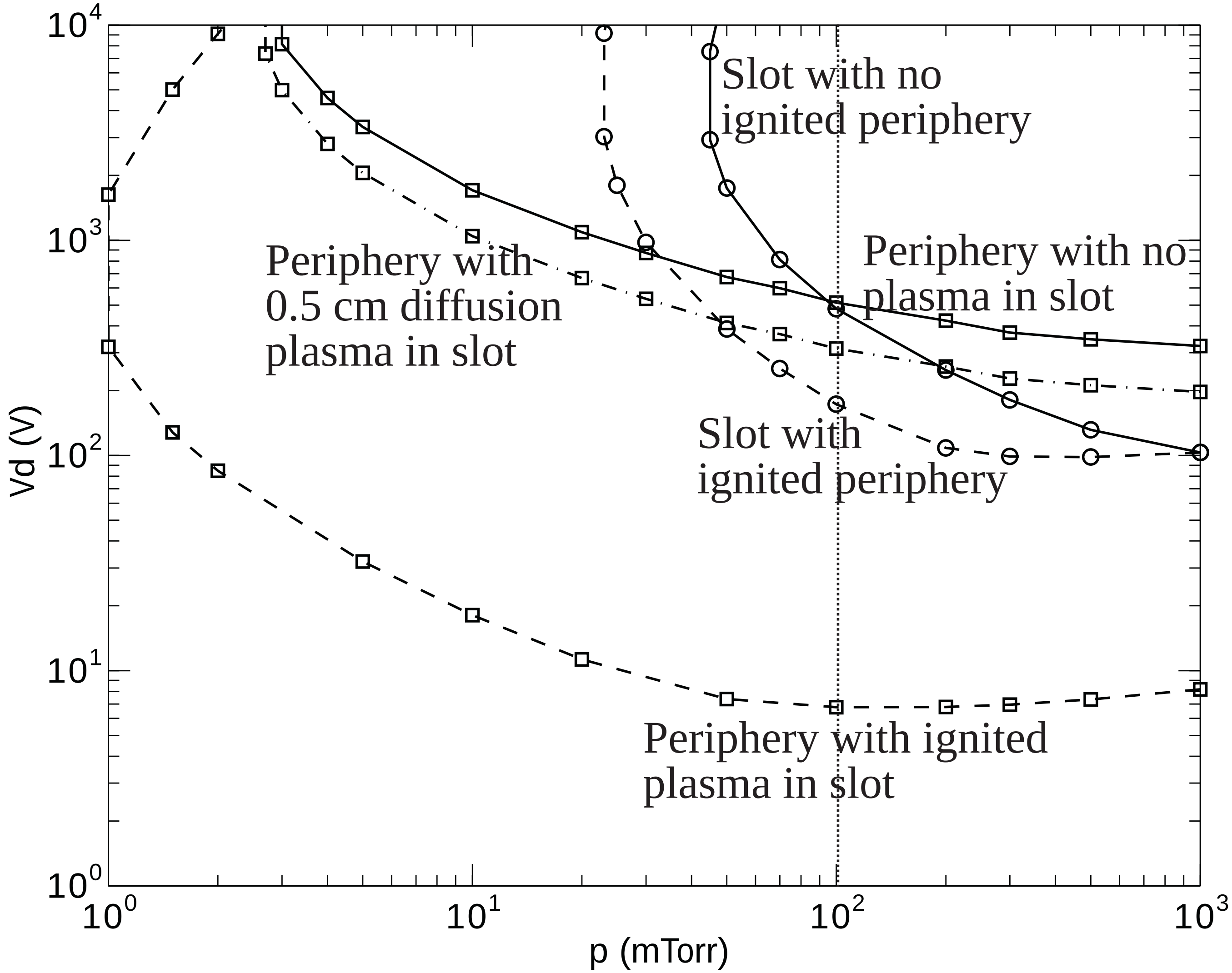
- Plot $\widetilde{V}_\mathrm{d}$ versus pressure for maintenance in slot and periphery

MAINTENANCE FOR NOMINAL PARAMETERS



- At 100 mTorr, slot ignites, then periphery ignites

HALVE GAP SIZE TO 0.25 CM



- Now at 100 mTorr, periphery ignites, then slot ignites

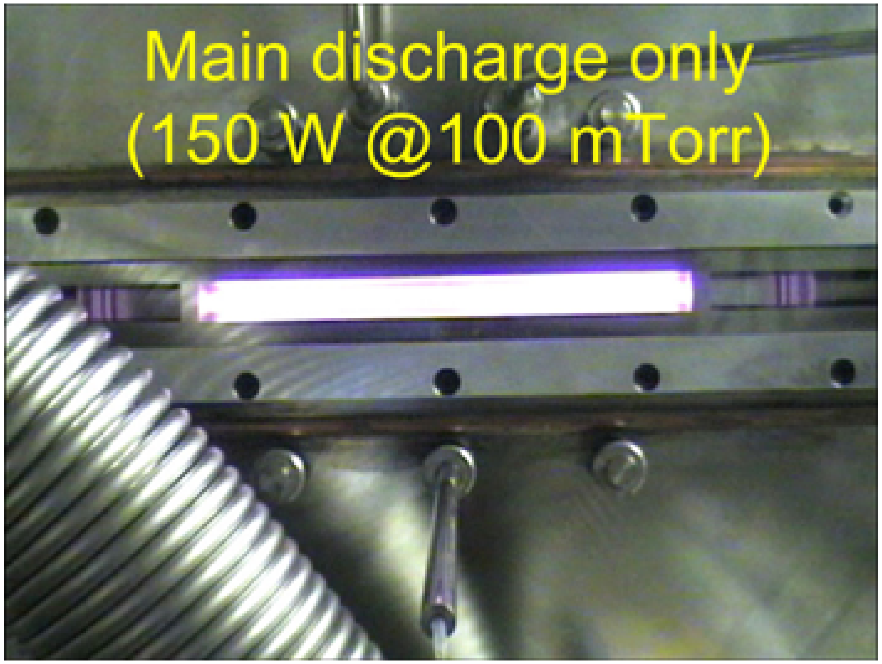
BERKELEY EXPERIMENT

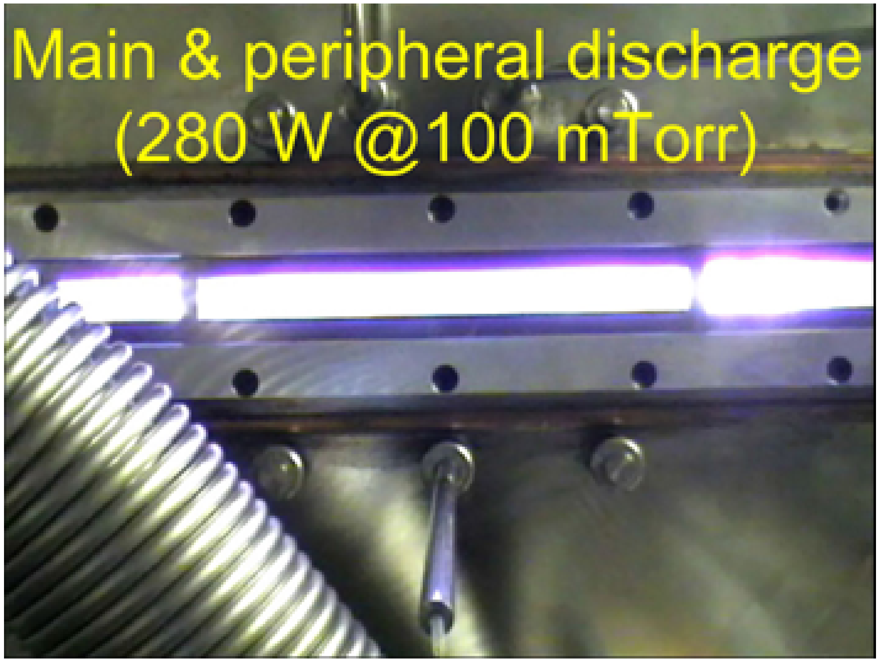
Sungjin Kim
J.T. Gudmundsson
Sangsup Jeong

CONFINED AND UNCONFINED PLASMA

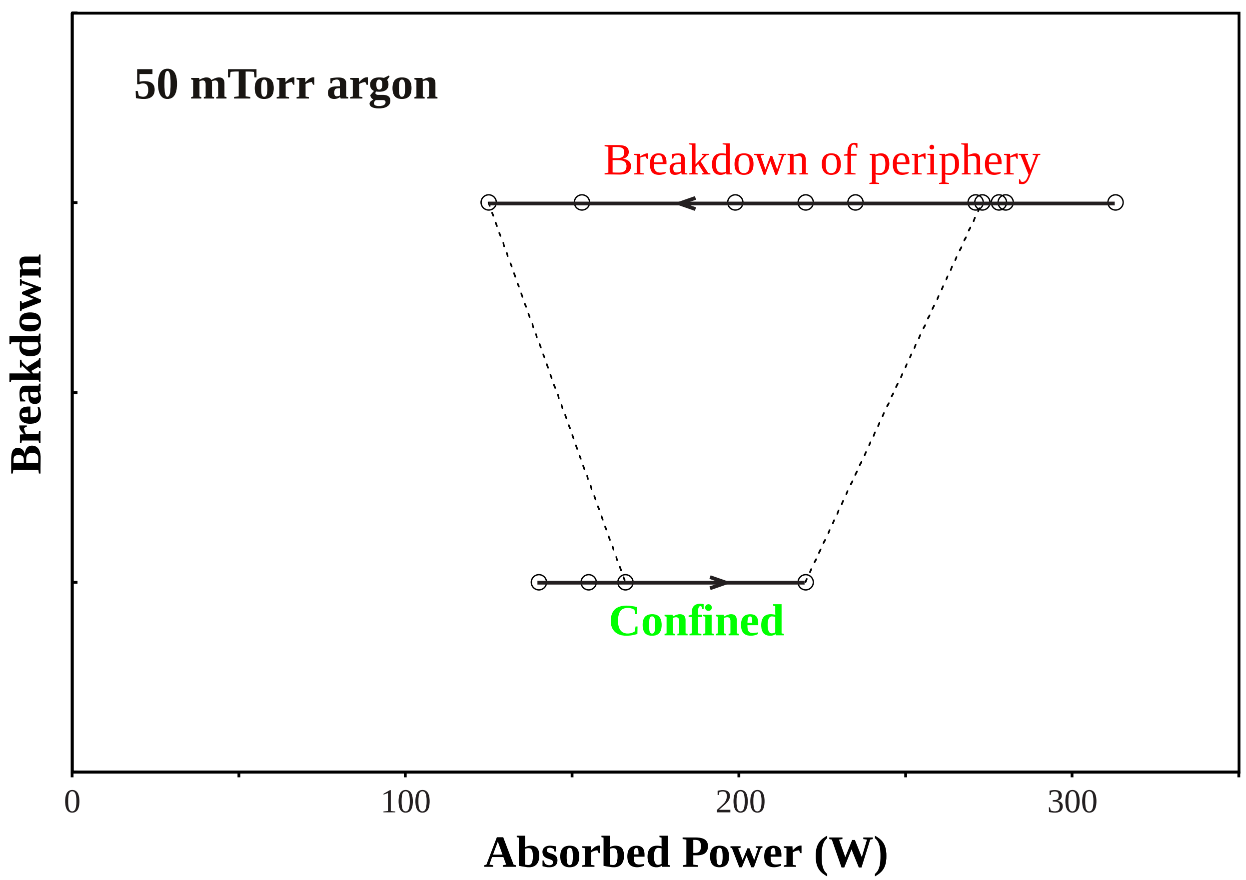
- 27 MHz, 5 ″ diameter powered electrode, 1/4″ slot gap g

(View through window along a diameter of the grounded electrode)



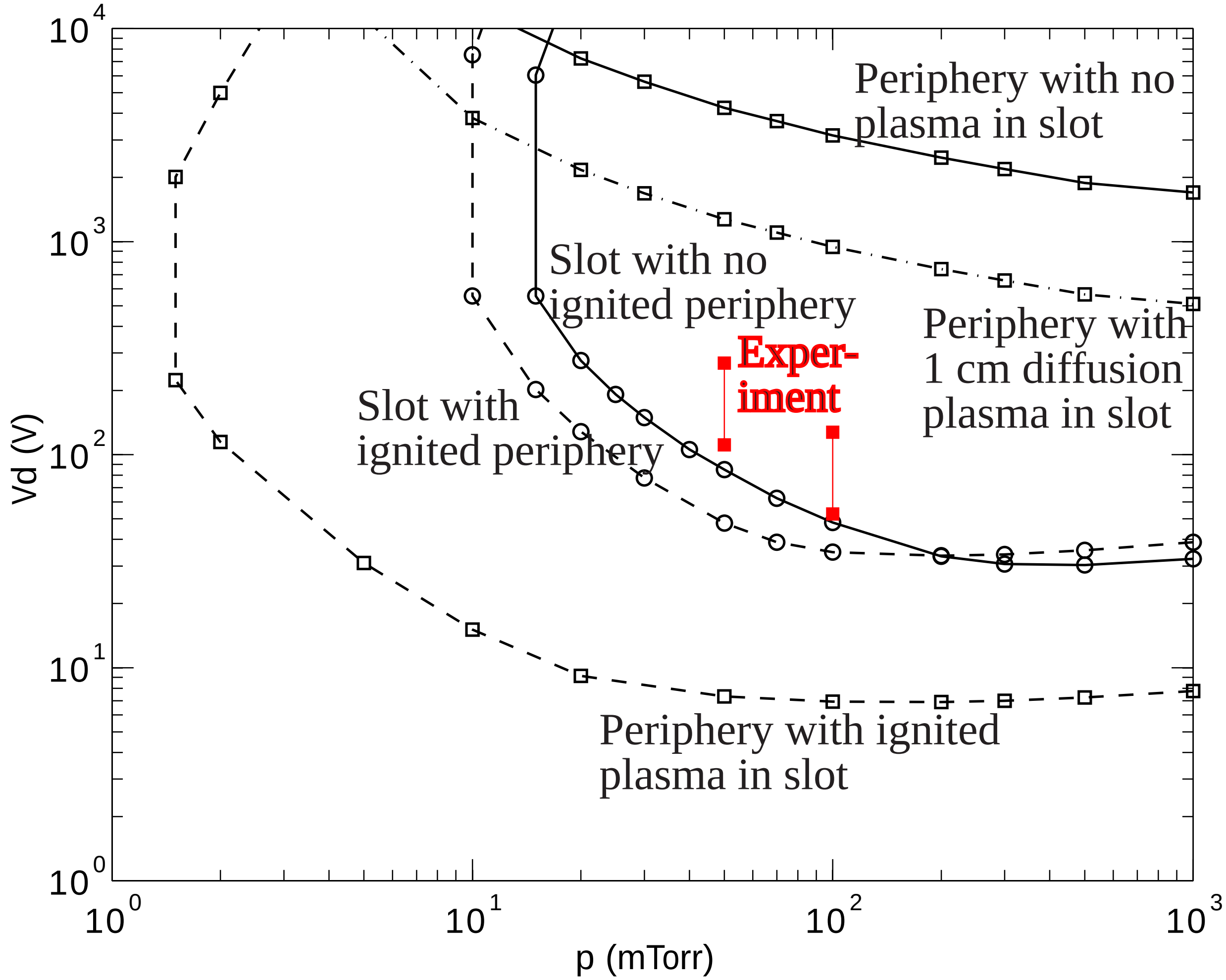


HYSTERESIS IN POWER CHARACTERISTICS



MAINTENANCE IN BERKELEY EXPERIMENT

- $l = 2.54$ cm, $g = 0.635$ cm, $w = 3.8$ cm, $w_{\text{per}} = 5.1$ cm

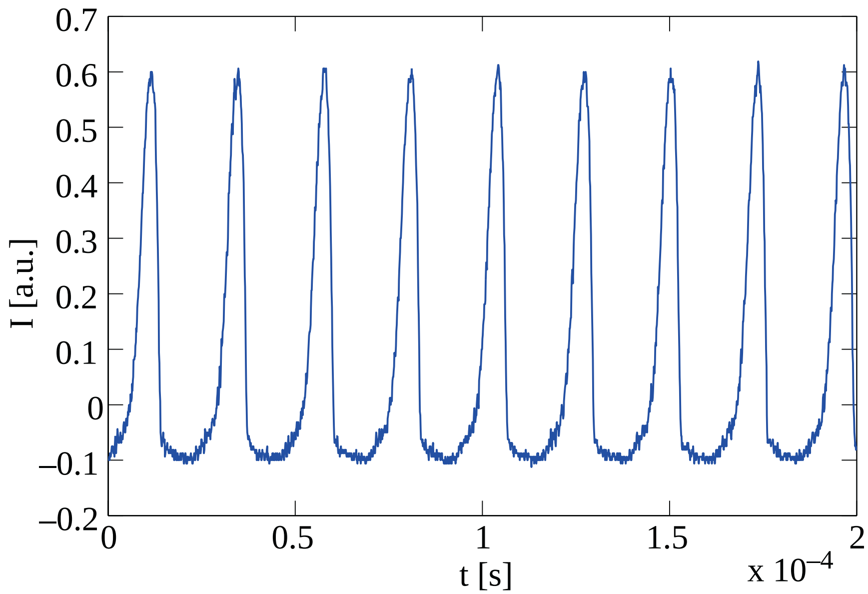


ConfinedPhys26Jul04

INSTABILITIES WITH PERIPHERAL PLASMA

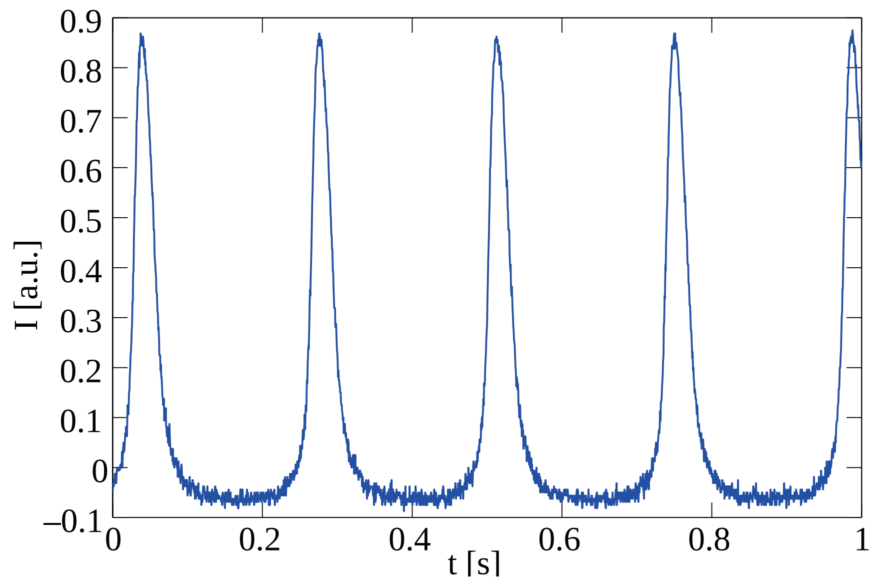
- 748.7 nm argon optical emission line in main discharge (the zero of I is not calibrated)

80 W, 100 mTorr



High frequency (43.3 kHz) relaxation oscillation

202 W, 77 mTorr



Low frequency (4.2 Hz) relaxation oscillation

FUTURE PLANS

- Measure the rf voltage on main discharge plasma
- Experimentally characterize single frequency ignition (27 MHz) as a function of voltage, pressure, and gap spacing
- Experimentally characterize dual frequency ignition (27/2 MHz)
- Experimentally characterize instabilities and develop theoretical model
- Model effect of aspect-ratio of periphery on maintenance
- Model the effect of transport of electrons past pinch-off on peripheral ignition
- Model “breakdown” of periphery for no plasma in slot