UNIVERSITY of HOUSTON

Initial Measurements and Modeling of a Novel Reactor to Control Plasma Electron and Ion Distribution Functions

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Plasma Science Center
Predictive Control of Plasma Kinetics

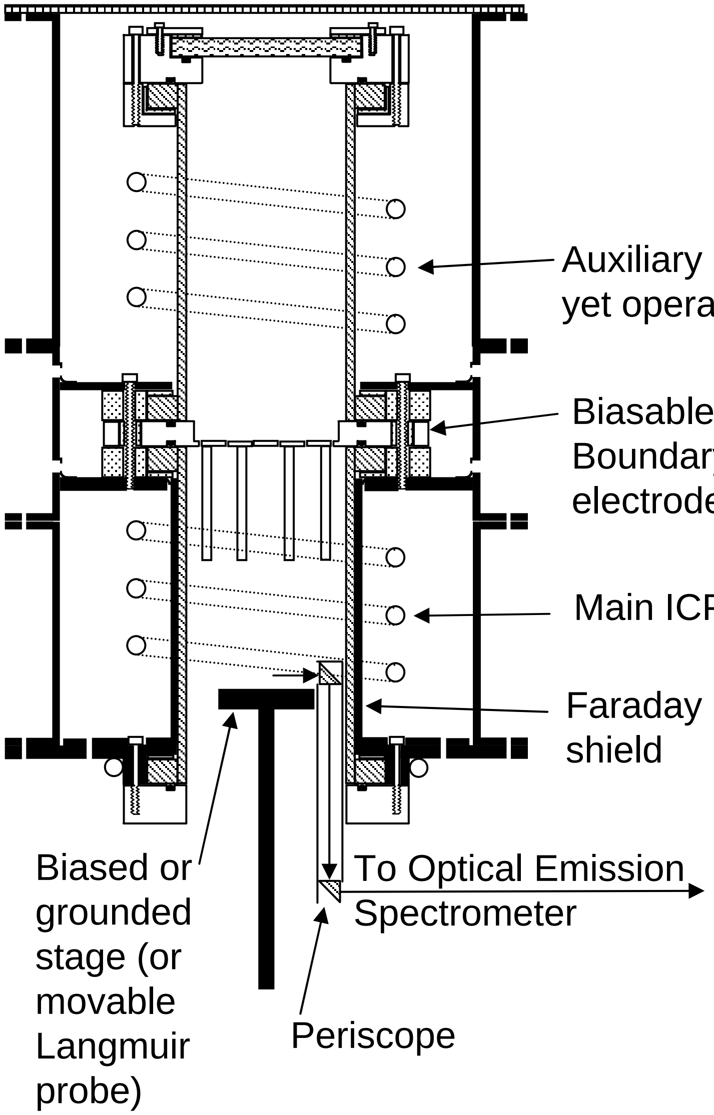
Part 1: Experimental Studies

Motivations

- Control electron and ion energy and angular distributions through manipulation of plasma power modulation, boundary electrode voltages and charged particle and/or metastable injection.

- Further develop and validate the trace rare gases optical emission spectroscopy (TRG-OES) method for measurements of EEDFs (especially at high energies) and then make the method available to the center.

Plasma Reactor for Advanced Control of IEDFs and EEDFs



Features

- Pulsed rf power at 13.56 MHz delivered to lower plasma source.

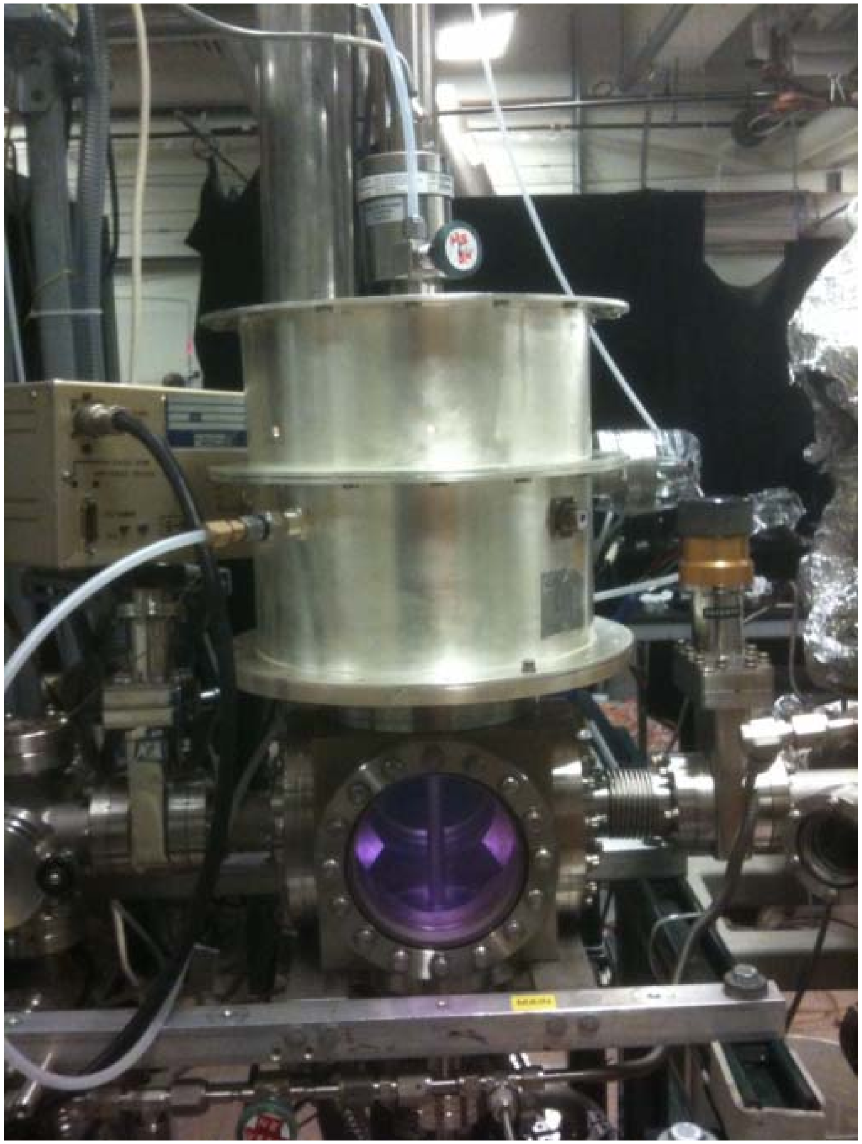
- Faraday shield to eliminate rf plasma potential.

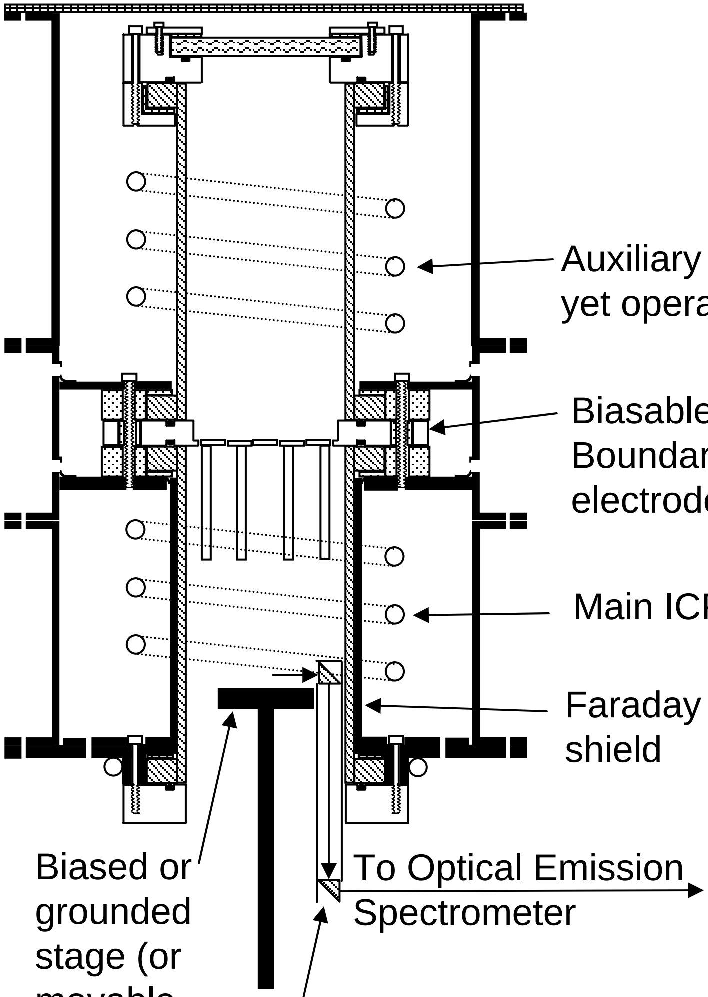
- Bias on boundary electrode controls the plasma potential.

- Ion energy controlled by either boundary electrode or substrate bias, or both.

- Top plasma source ignites and/or injects ions, electrons, radicals, metastables, etc into the lower plasma.

Plasma Reactor for Advanced Control of IEDFs and EEDFs





Auxiliary ICP (not yet operational)

Biasable Boundary electrode

Main ICP

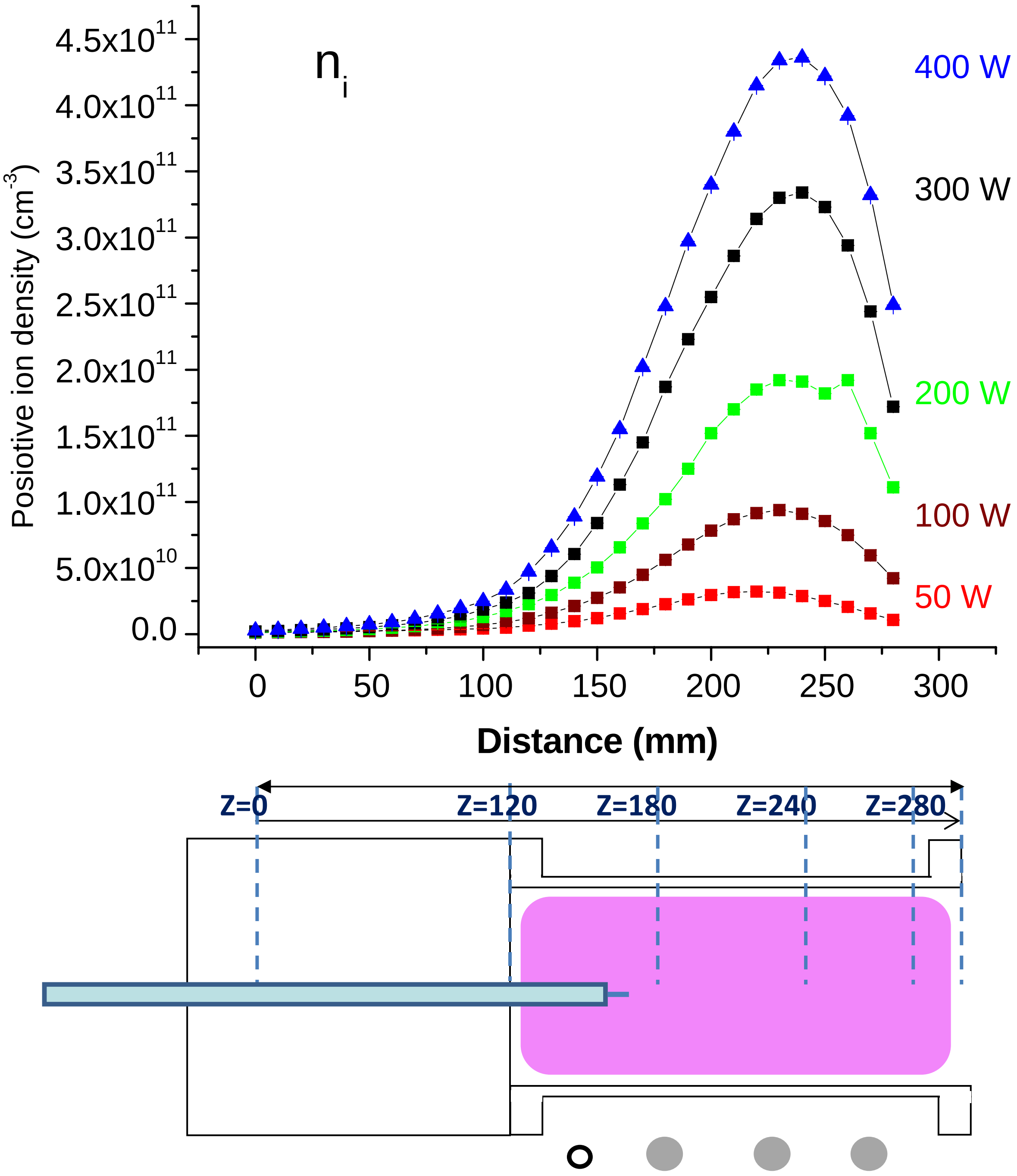
Faraday shield

Biased or grounded stage (or movable Langmuir probe)

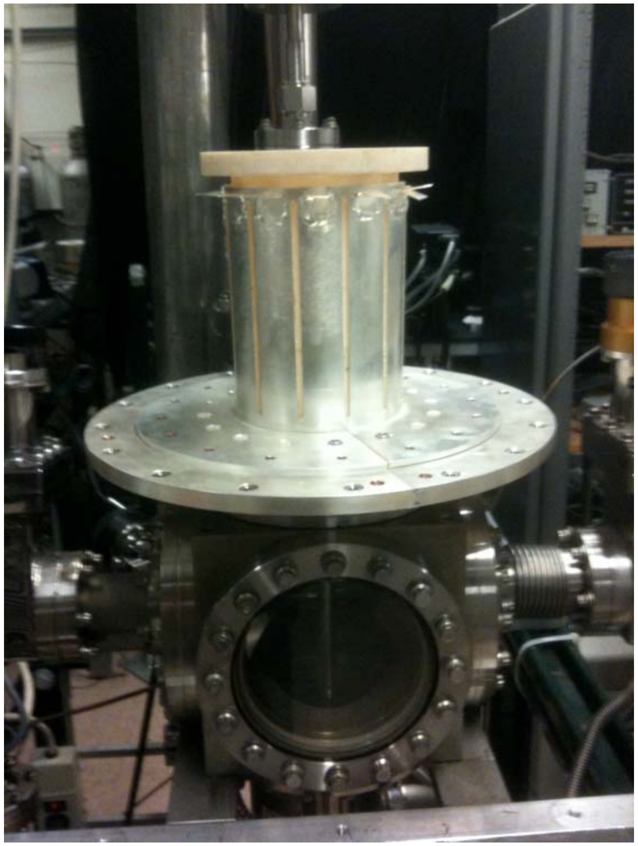
To Optical Emission Spectrometer

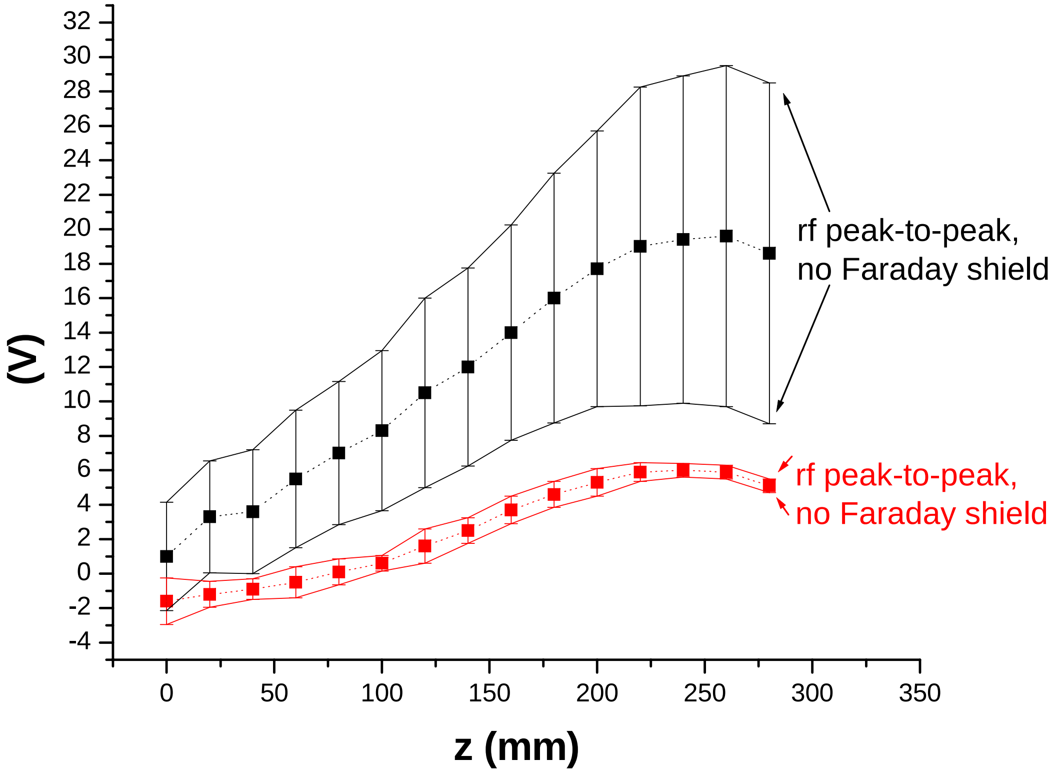
Periscope

Langmuir probe measurements of positive ion densities in a 10 mTorr, 40 sccm Ar plasma.



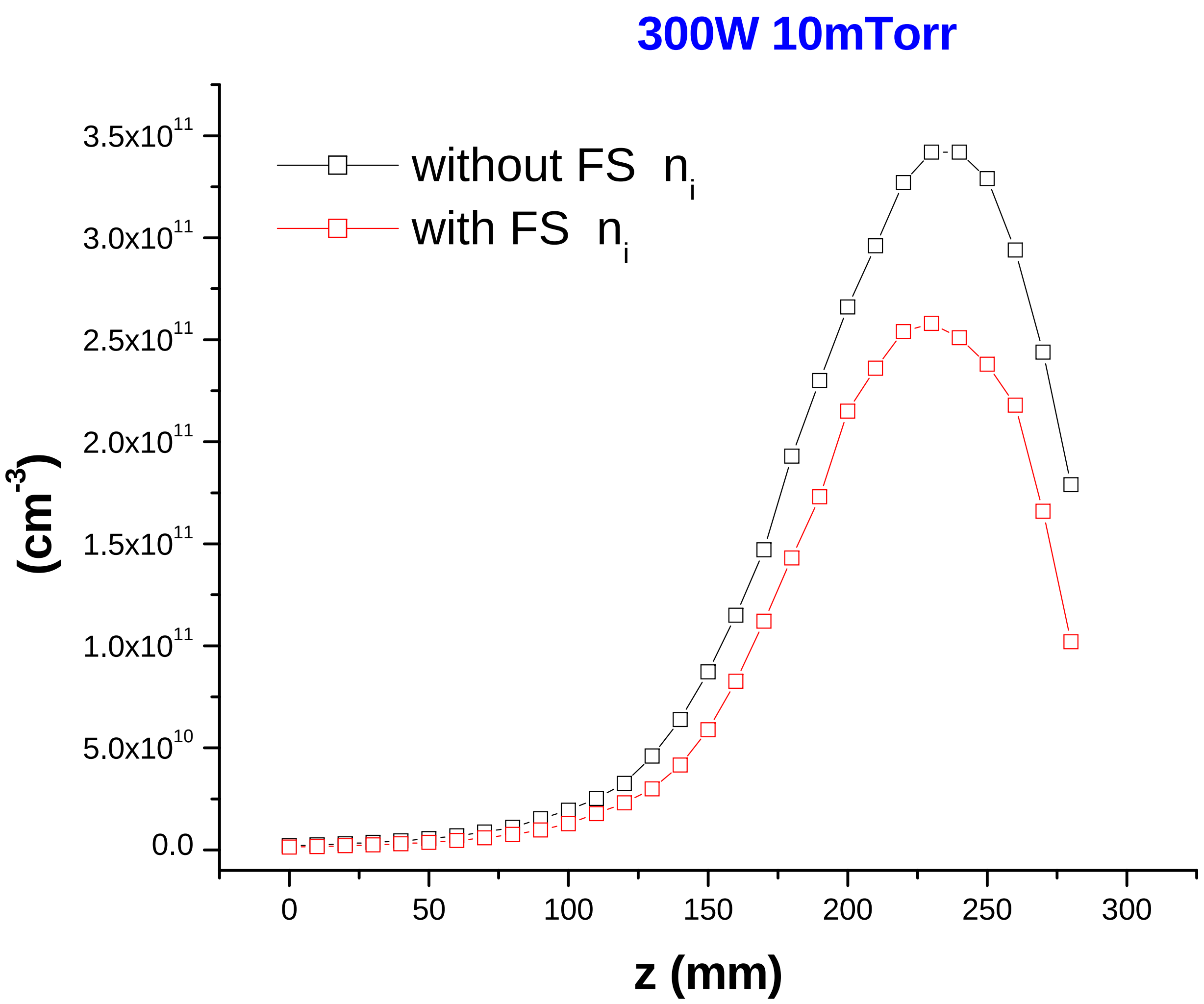
Faraday Shield



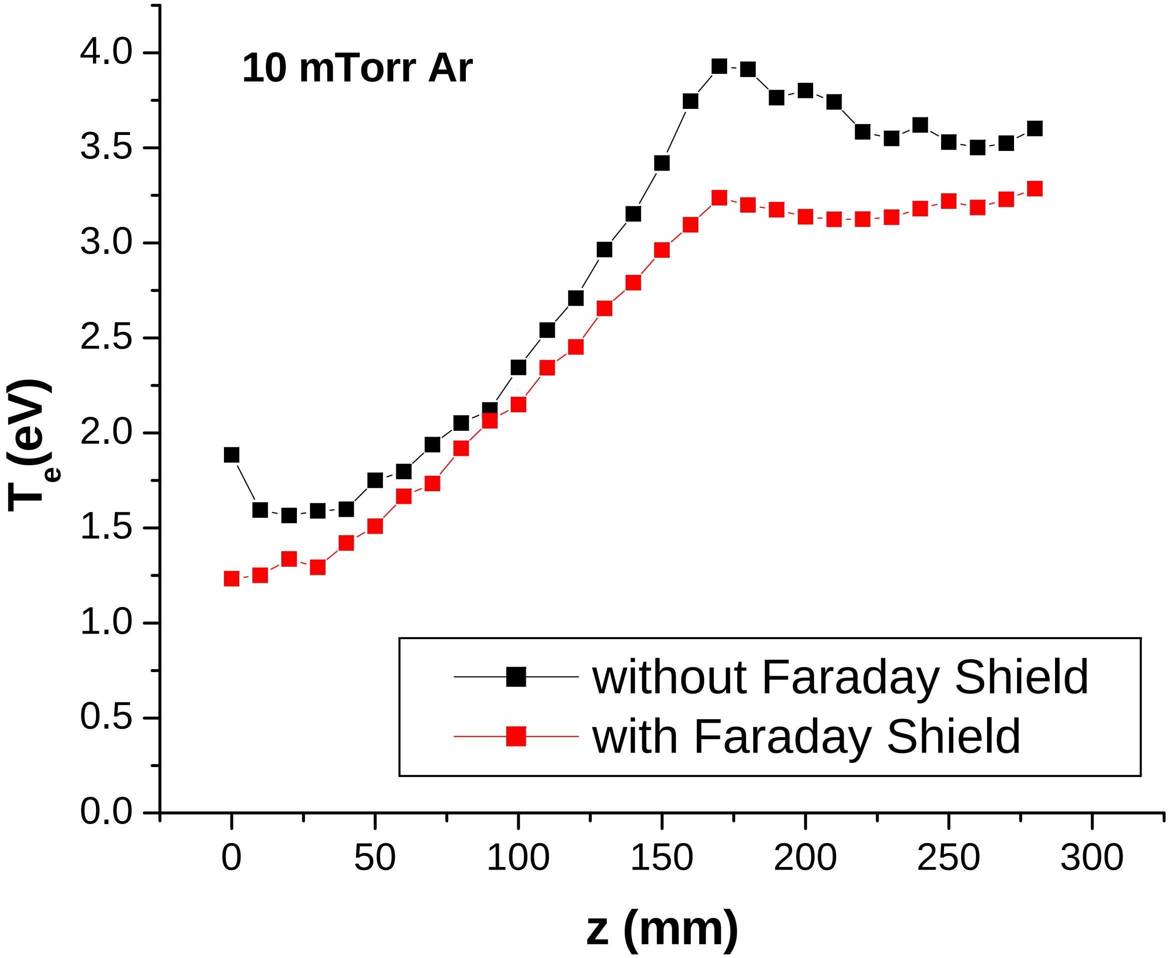


- rf plasma potential measured on the “reference electrode” of the Langmuir probe.
- Faraday shield virtually eliminated the rf plasma potential – hence sharper IEDF
- Faraday shield also reduced the DC floating potential.

Effect of Faraday Shield on Plasma Density

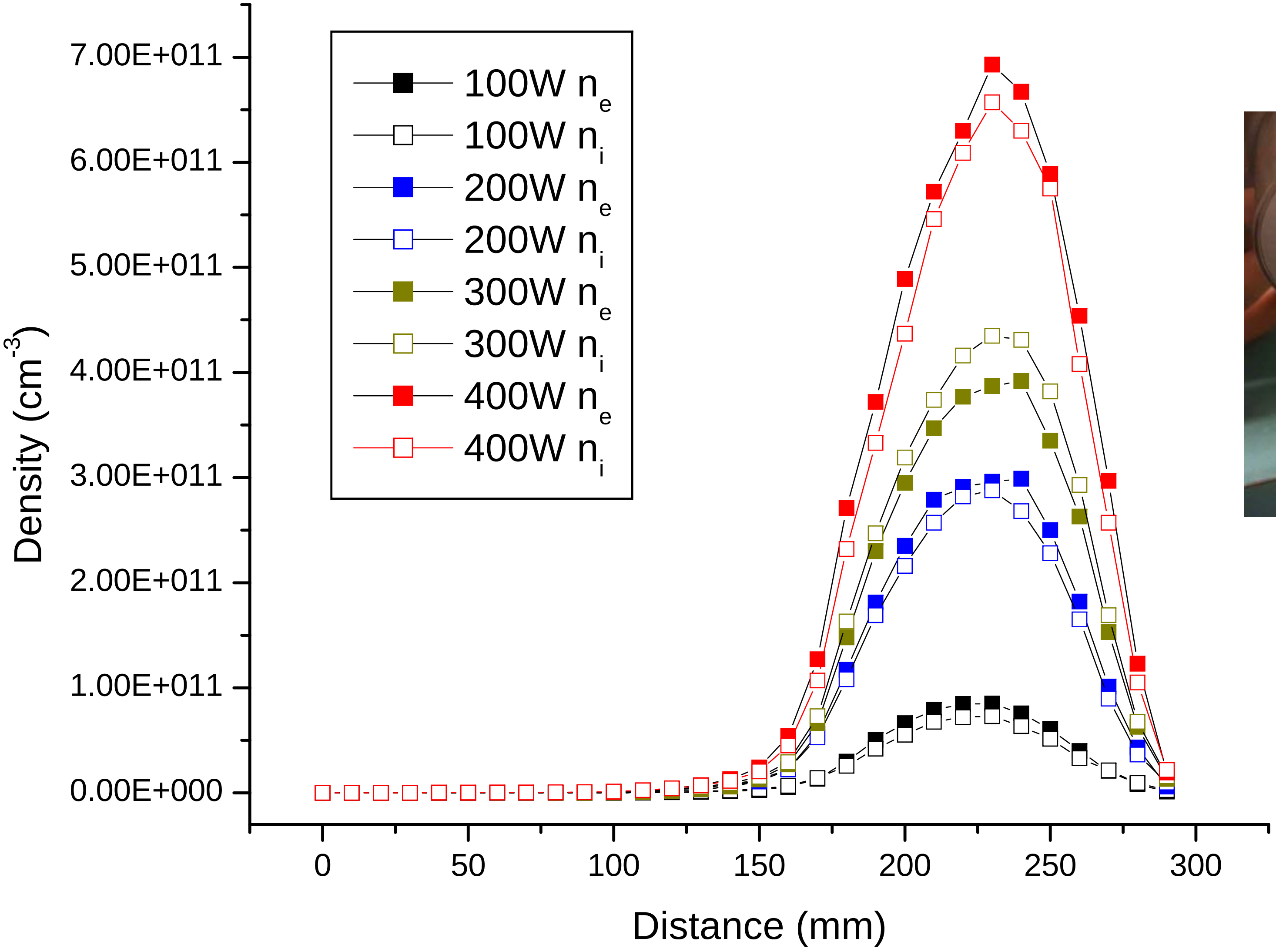


T_e comparison with and without Faraday Shield

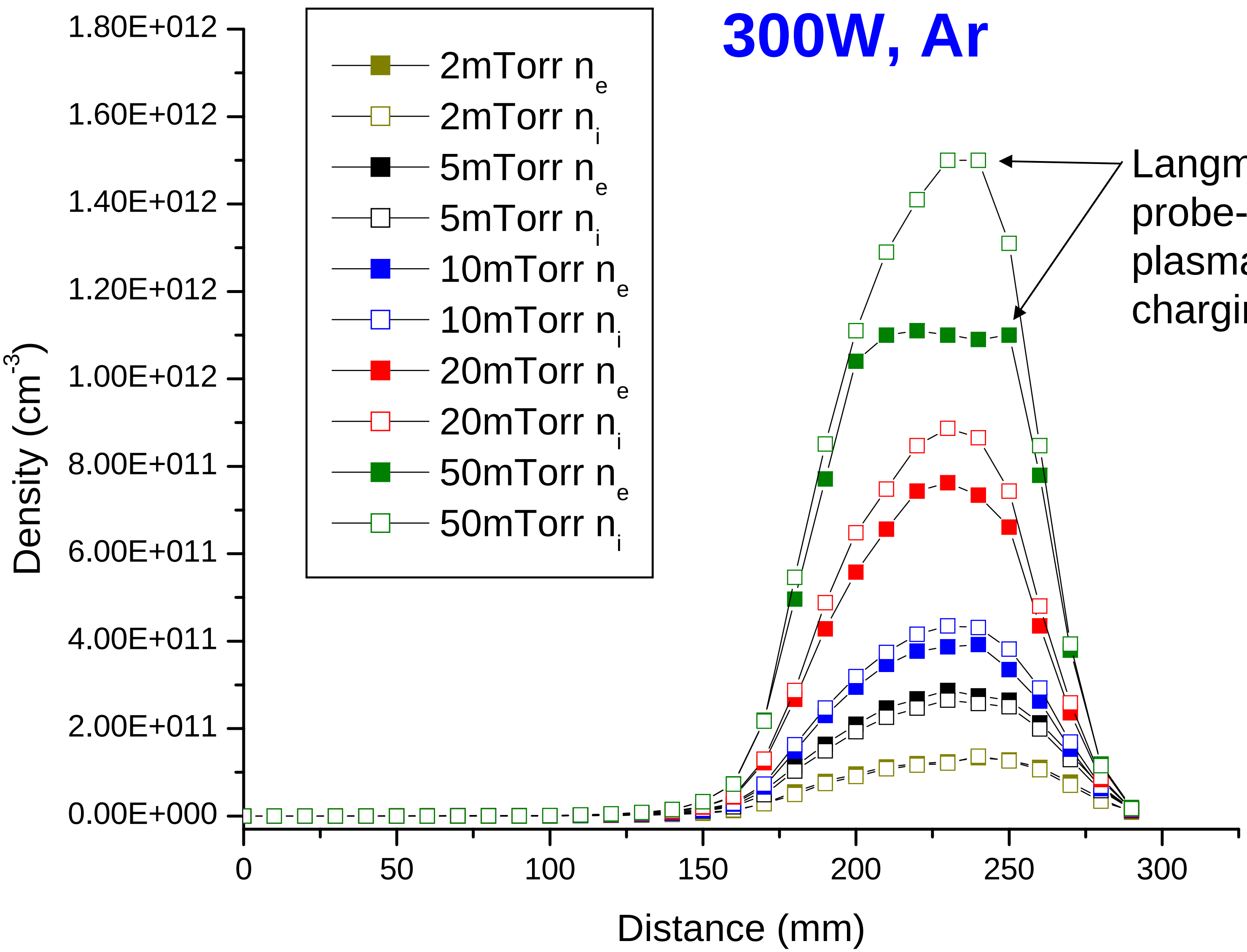


n_e and n_i as a Function of Power

10mTorr Ar



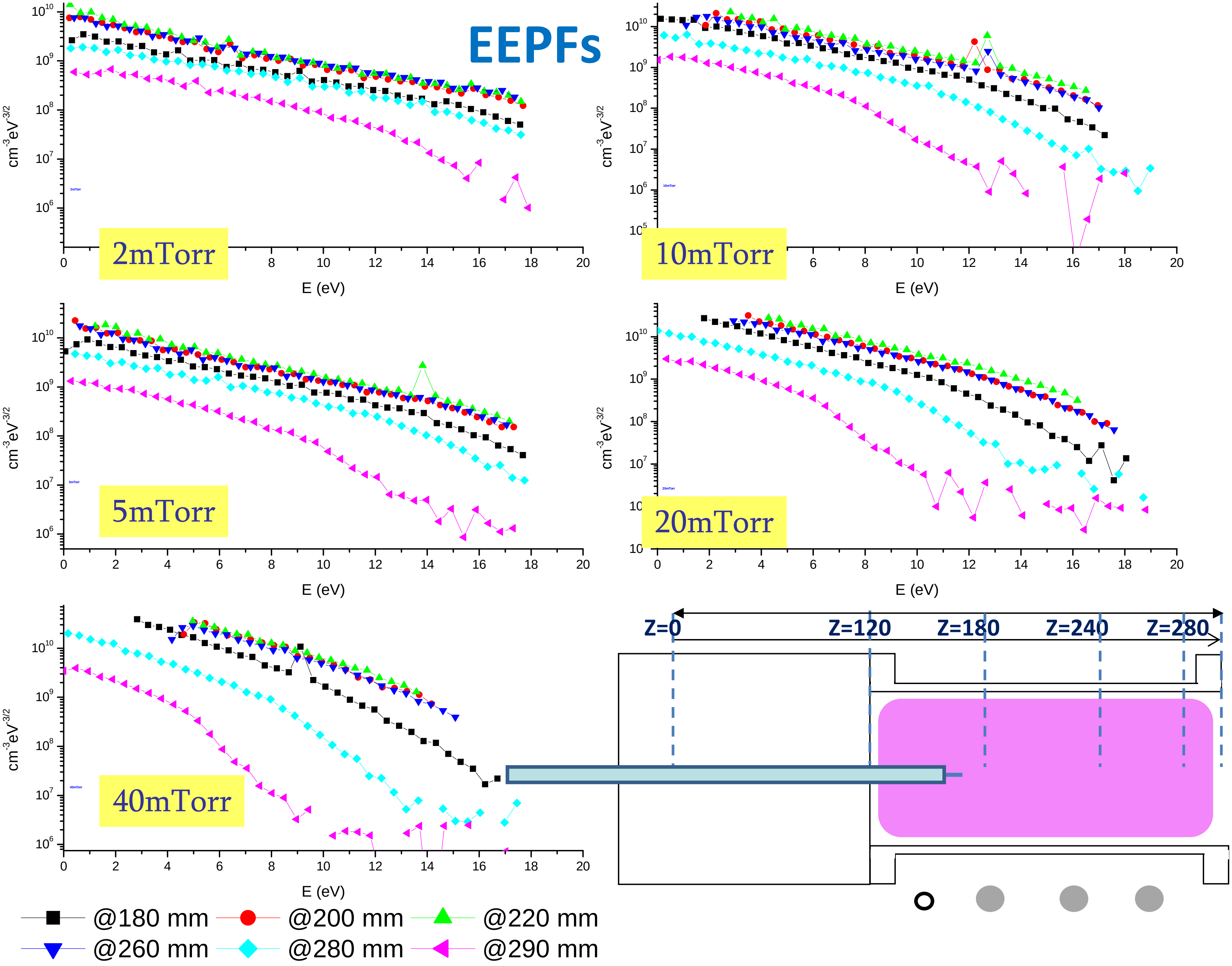
n_e and n_i as a Function of Pressure



300W, Ar

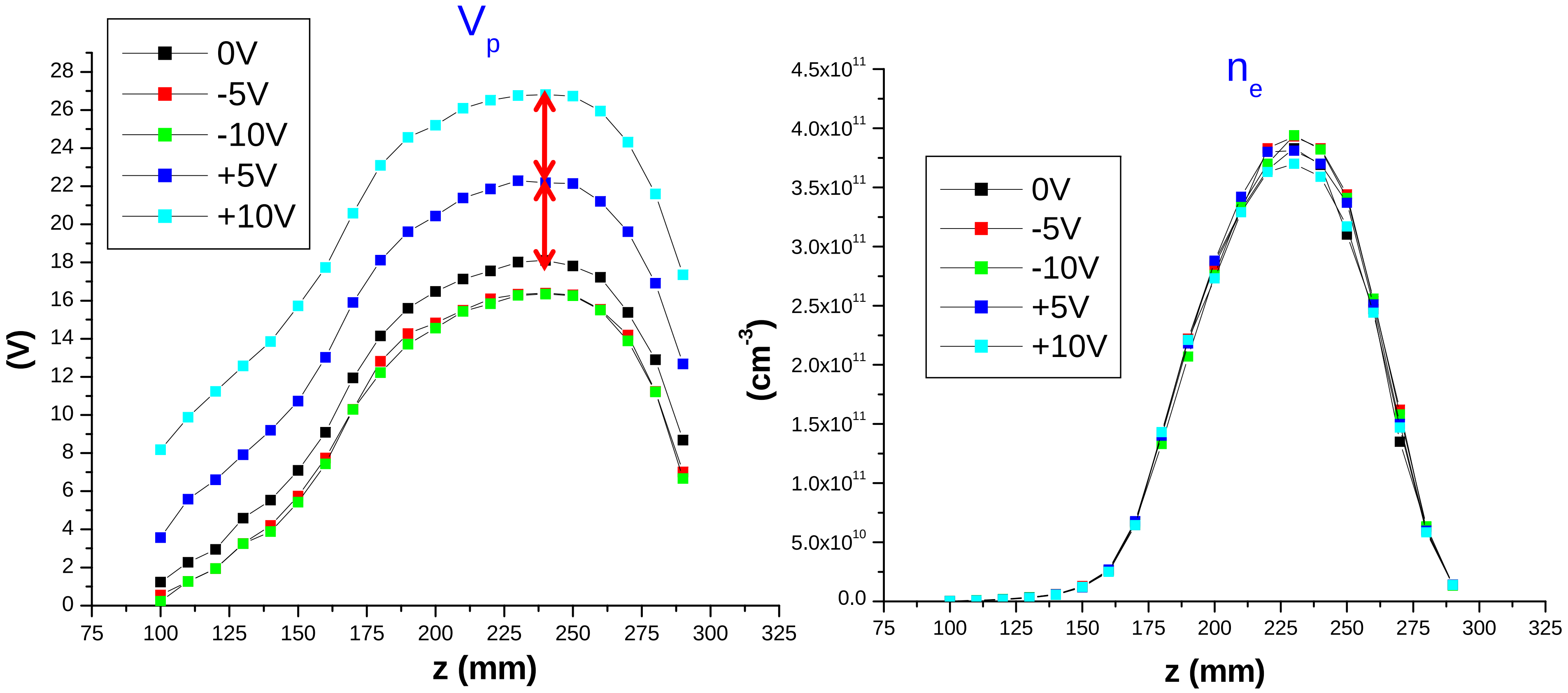
Langmuir probe-induced plasma charging

EEPFs



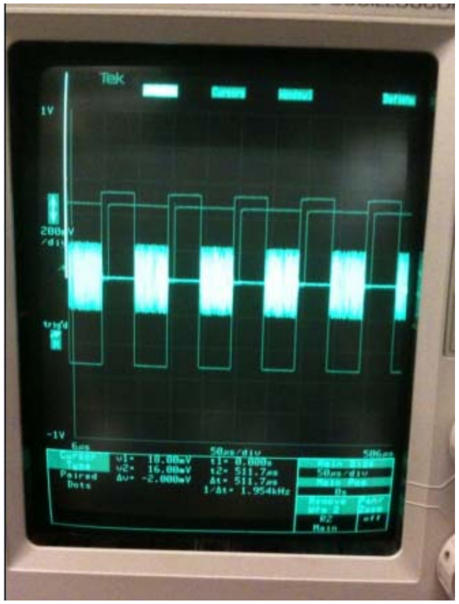
2mTorr
10mTorr
5mTorr
20mTorr
40mTorr
cm^{-3}eV$^{-3/2}$
E (eV)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
0
2
4
6
8
10
12
14
16
18
20
@180 mm
@200 mm
@220 mm
@260 mm
@280 mm
@290 mm
Z=0
Z=120
Z=180
Z=240
Z=280

V_p (and hence mean ion energy) control by biasing the boundary electrode



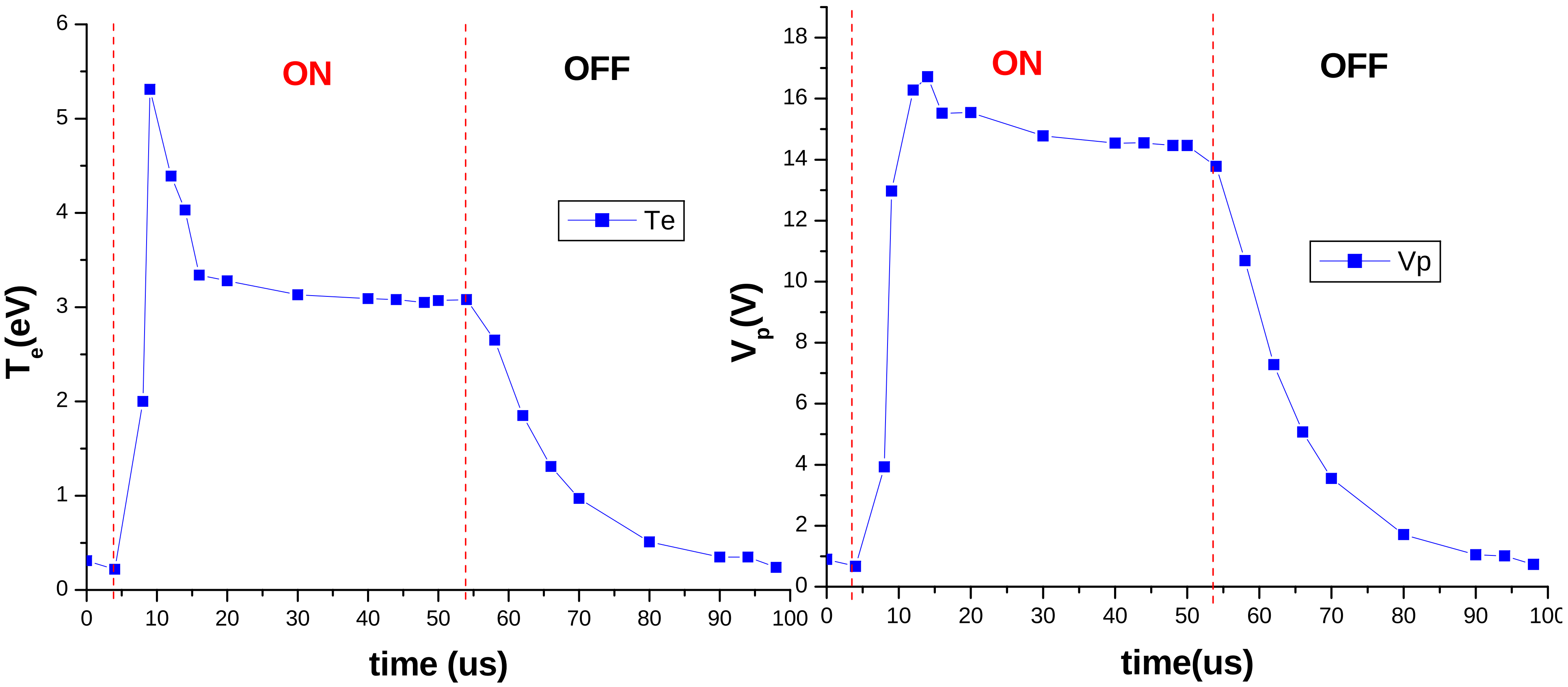
Pulsed plasma system

- 13.56 MHz power, 10kHz modulation frequency



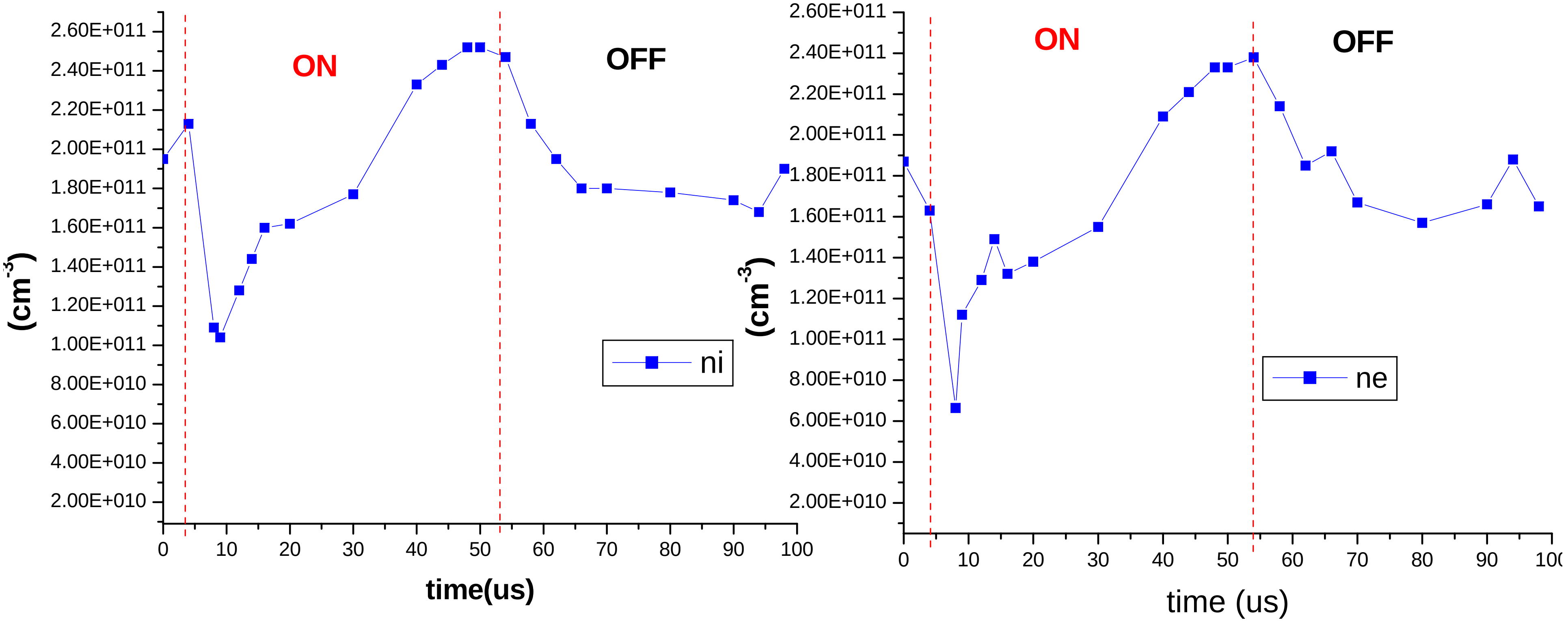
- Vary duty cycle
- Measure T_e, n_e, n_i^+, etc.
- Motivation: Reduce IEDF, IADF

T_e & V_p

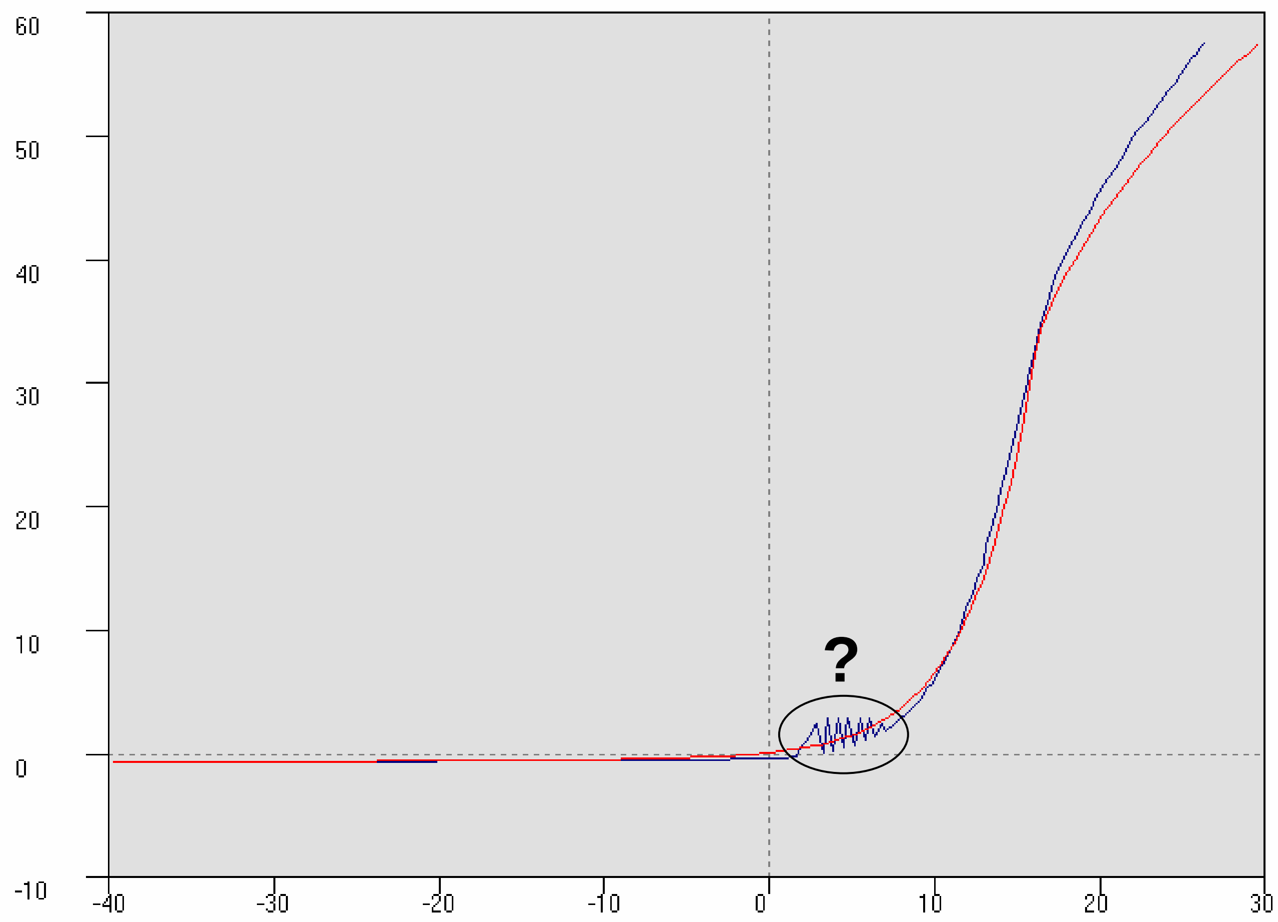


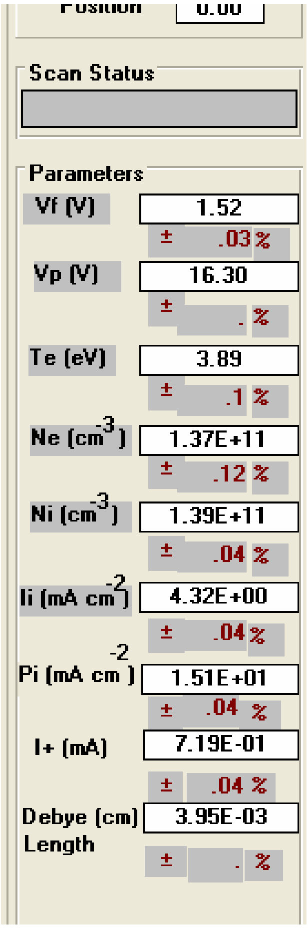
ON
OFF
Te
T_e(eV)
0
1
2
3
4
5
6
time (us)
0
10
20
30
40
50
60
70
80
90
100
ON
OFF
Vp
V_p(V)
0
2
4
6
8
10
12
14
16
18
time(us)
0
10
20
30
40
50
60
70
80
90
100

n_i & n_e


2.60E+011
2.40E+011
2.20E+011
2.00E+011
1.80E+011
1.60E+011
1.40E+011
1.20E+011
1.00E+011
8.00E+010
6.00E+010
4.00E+010
2.00E+010
(cm-3)
0
10
20
30
40
50
60
70
80
90
100
time(us)
ON
OFF
ni
2.60E+011
2.40E+011
2.20E+011
2.00E+011
1.80E+011
1.60E+011
1.40E+011
1.20E+011
1.00E+011
8.00E+010
6.00E+010
4.00E+010
2.00E+010
(cm-3)
0
10
20
30
40
50
60
70
80
90
10
time (us)
ON
OFF
ne

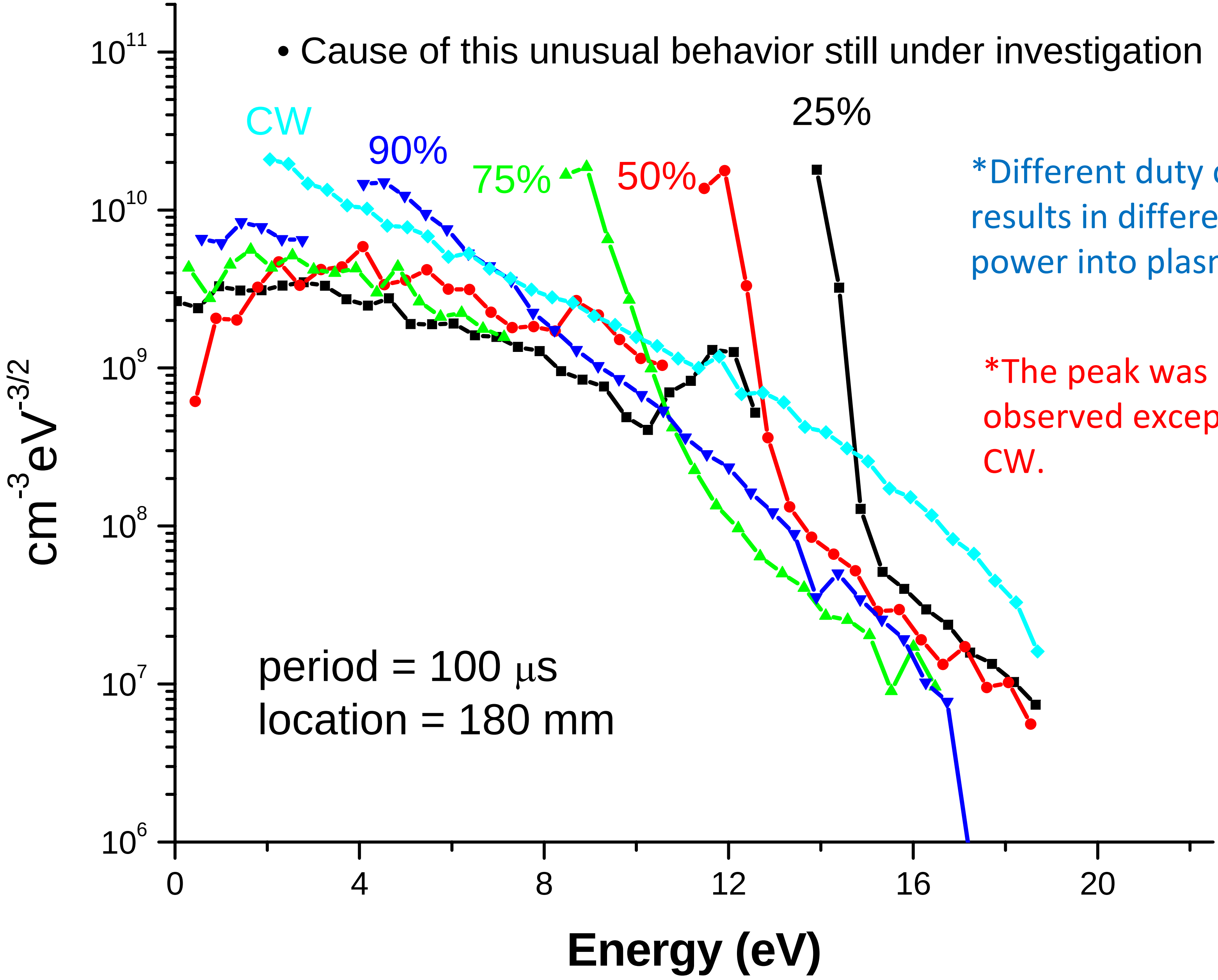
Unusual I-V Characteristics in the initial stages of the ON period under some conditions





Position	0.00	
Vf (V)	1.52	± .03 %
Vp (V)	16.30	± . %
Te (eV)	3.89	± .1 %
Ne (cm^{-3})	1.37E+11	± .12 %
Ni (cm^{-3})	1.39E+11	± .04 %
Ii (mA cm^{-2})	4.32E+00	± .04 %
Pi (mA cm^{-2})	1.51E+01	± .04 %
I+ (mA)	7.19E-01	± .04 %
Debye (cm) Length	3.95E-03	± . %

EEPFs @10us into ON cycle as a function of duty cycle



- Cause of this unusual behavior still under investigation

period = 100 μs
location = 180 mm

*Different duty cycle results in different avg. power into plasma.

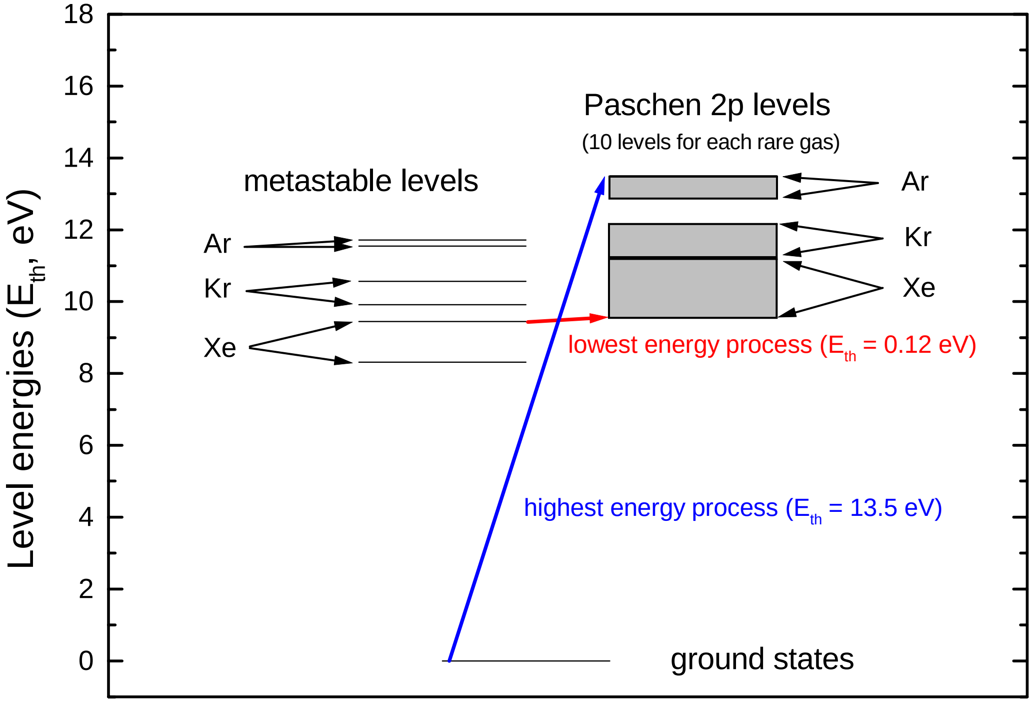
*The peak was observed except for CW.

Trace Rare Gases Optical Emission Spectroscopy (TRG-OES)

- Add non-perturbing traces (1% each) of Xe, Kr, Ar, and Ne to the process gas.

- T_e and even EEDFs derived from optical emission from the Paschen 2p levels.

- T_e is determined from a comparison of measured intensities with relative intensities computed from a model, with T_e or the EEDF as an adjustable parameter.



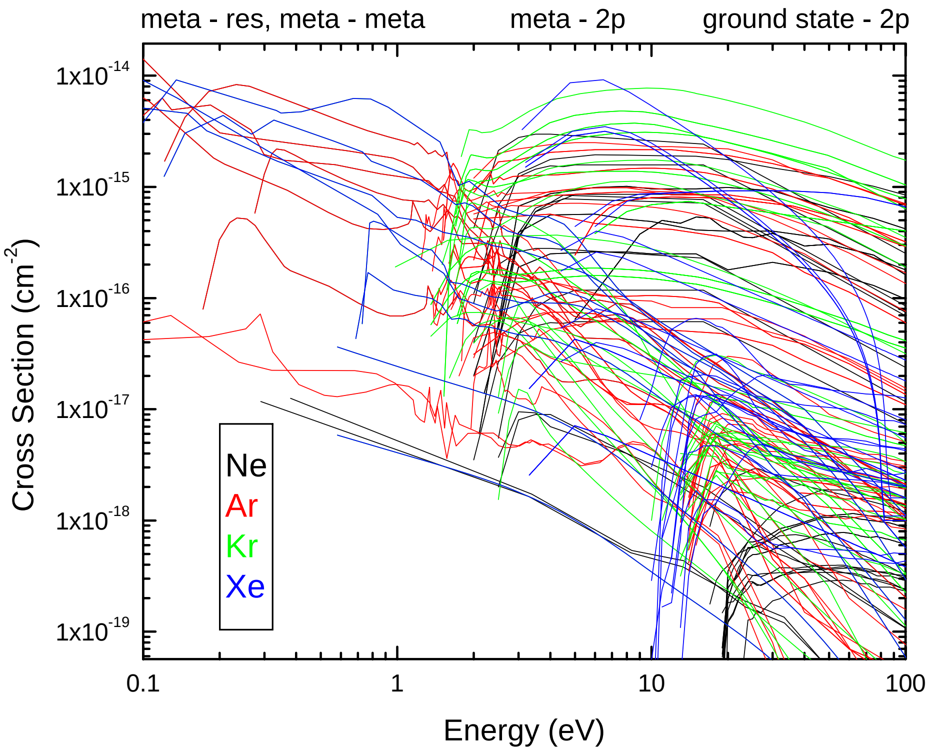
- <u>See review article</u>: “Plasma Electron Temperatures and Electron Energy Distributions Measured by Trace Rare Gases Optical Emission Spectroscopy”, J. Phys. D.: Appl. Phys. **37**, R217 (2004).

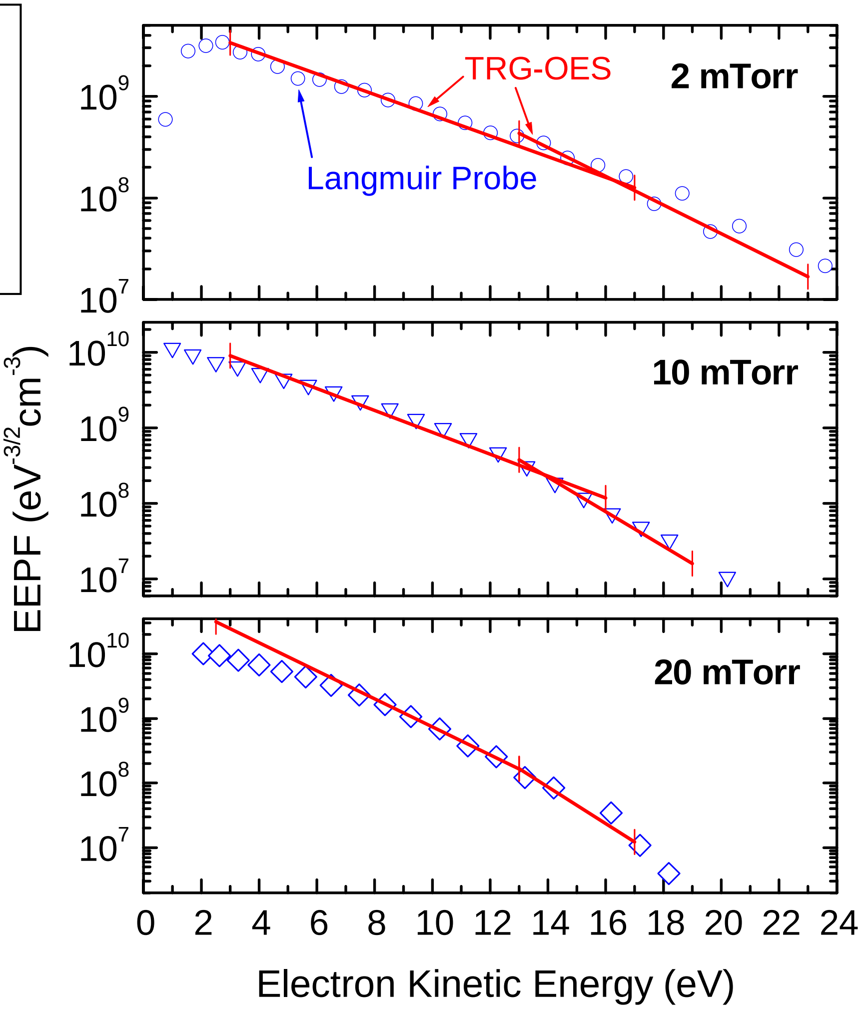
Comparison of EEDFs in Cl_2 Plasma Measured with a Langmuir Probe and Derived from TRG-OES

- Current method: select lines that probe different e-energies and obtain “T_e”. Piece together EEDF from different T_es.

- Futher development: **1)** use function instead of Maxwellian EEDF, **2)** use matrix method.

Rare gas e-impact cross sections





Summary

- Novel reactor partially completed and successfully tested.
- Behavior as expected except for unusual oscillation in I-V characteristic during initial portion of ON cycle of pulsed ICP.

Future Work

- Investigate other rare gases, molecular gases
- Invoke full capabilities of the reactor (vary boundary voltage, pulsing of both ICPs, etc) and measure IEDFs.
- Explore injection of upper plasma into lower plasma for influencing EEDF.
- Begin TRG-OES validation and collaborations with center members

Part 2: Modeling and Simulations

Goals and Approach

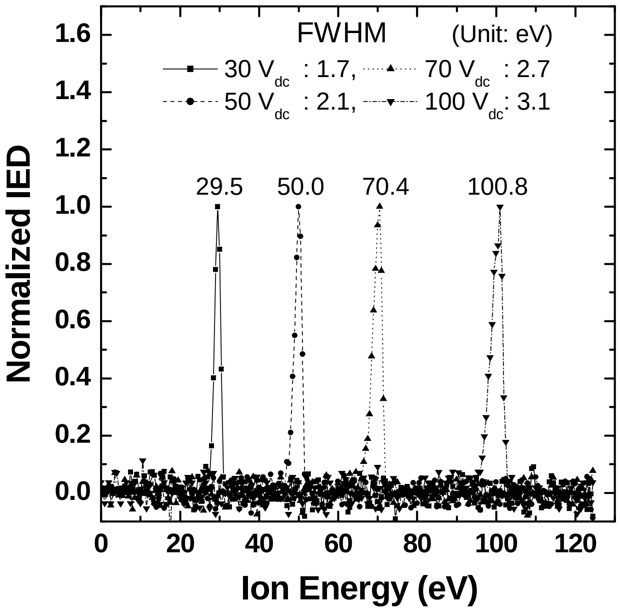
- **General Goal**: **Develop methodologies to achieve "tailored" plasma electron and ion energy distribution functions (EEDFs and IEDFs).**

- Focus of this presentation is IEDFs.
  - **Conventional problem**: **Given the plasma operating parameters, predict or measure the resulting IEDF.**
  - **Inverse problem**: **Given a desired IEDF, predict or establish the plasma operating parameters that will yield that IEDF.**

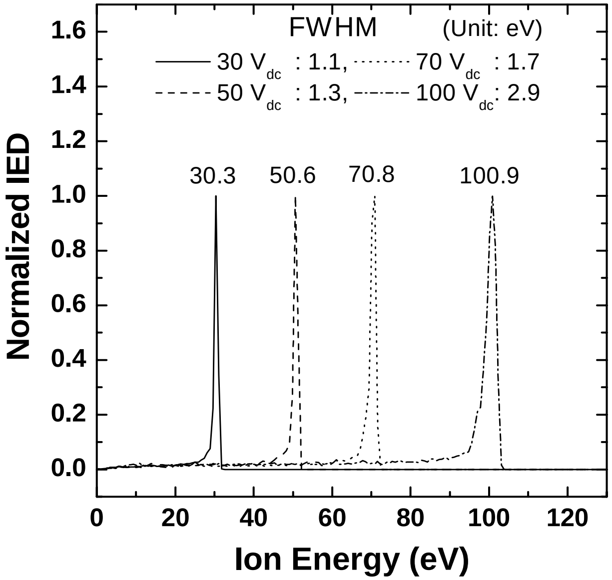
- Ultimate goal is solution of the inverse problem.
- Use combination of experiments and modeling/simulation.
- Modeling is semi-analytic.
- Simulation is PIC using in-house codes (Nam, Economou and Donnelly, PSST*,* **16**, 90 (2007)) or PDP1 (Verboncoeur, Alves, Vahedi, Birdsall, *J. Comp. Phys*., **104**, 321 (1993)).

“Tailored” Ion Energy Distributions

Pulsed plasma with synchronous application of a boundary voltage, allow the generation of a nearly monoenergetic IEDF with controlled energy.



Experiment: Xu, Economou, Donnelly and Ruchhoeft, *Appl. Phys. Lett.*, 87, 041502 (2005).



PIC Simulation: Nam, Economou, and Donnelly, *Plasma Sources Sci. Technol.*, 16, 90 (2007).

Pulsed Plasma can also Improve Ion Directionality

$$\theta_{IAD} \sim \arctan\left(\frac{kT_{i,sh}}{eV_{sh}}\right)^{1/2}$$

Assumes collisionless sheath

θ_{IAD} : Ion angular distribution at substrate

$T_{i,sh}$: Ion temperature in the plasma sheath edge

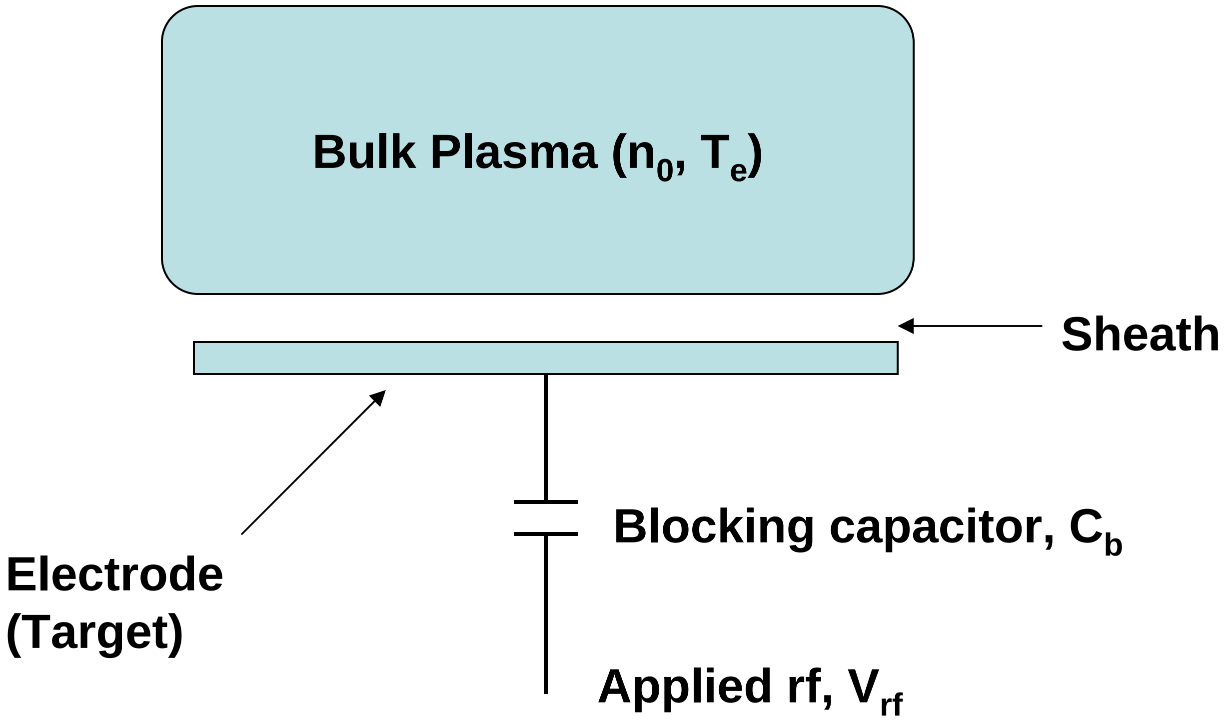
V_{sh} : Sheath potential

T_i^{sh} scales with T_e →

Lower T_e can improve the directionality of ions

Electrode Immersed in Semi-infinite CW Plasma

Plasma density and electron temperature are not affected by electrode potential



Bulk Plasma (n_0, T_e)

Sheath

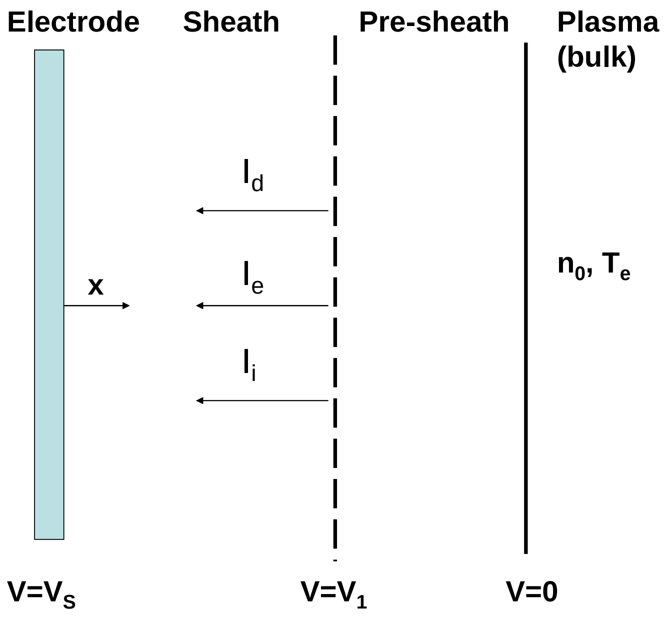
Electrode (Target)

Blocking capacitor, C_b

Applied rf, V_{rf}

Semi-analytic Model (cont.)

Schematic of the sheath region



1. Electrode immersed in semi-infinite plasma of given electron (ion) density and electron temperature.
2. Electron, ion and displacement currents flow through the sheath.
3. Non-linear sheath capacitance C_s is calculated from the electric field at the electrode, E.

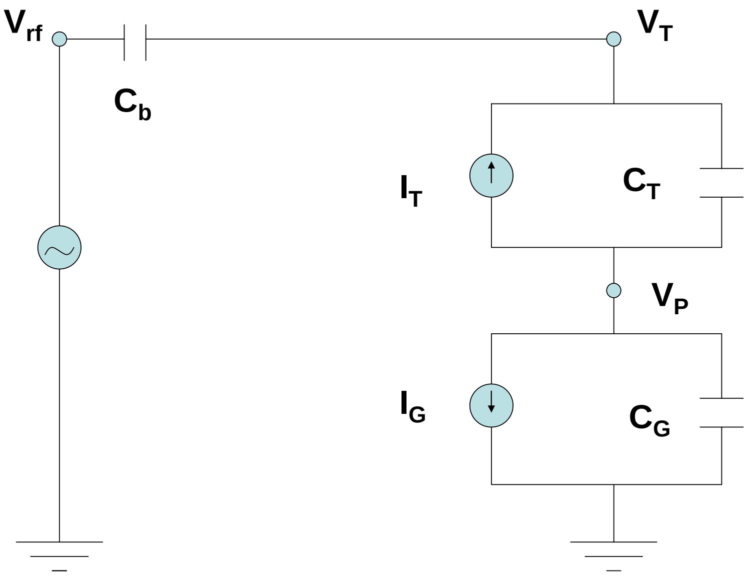
$$C_s = -\varepsilon_0 A \frac{\partial E}{\partial V_s}$$

$$E = -\sqrt{\frac{2n_1 kT_e}{\varepsilon_0}}[exp(\frac{e(V_s - V_1)}{kT_e}) + \frac{V_s}{V_1} - 2]^{1/2}$$

A. Metze et al., *J. Appl. Phys*., **60**, 3081 (1986).
P. Miller and M. Riley, *J. Appl. Phys*., **82**, 3689 (1997).
T. Panagopoulos and D. Economou, *JAP*, **85**, 3435 (1999).

Semi-analytic Model (cont.)

- Equivalent circuit, see A. Metze et al., *J. Appl. Phys*., **60**, 3081 (1986).



Subscripts T and G refer to “target” and “ground” electrodes, respectively.

$$C_b \frac{d}{dt}(V_{rf} - V_T) + C_T \frac{d}{dt}(V_P - V_T) + I_T = 0$$

$$C_T \frac{d}{dt}(V_P - V_T) + C_G \frac{d}{dt} V_P + I_T + I_G = 0$$

$$\frac{dV_d}{dt} = -\frac{V_d - V_T}{\tau_i}$$

Ions respond to
a “damped” potential V_d

Desired voltage V_{rf} is applied through blocking capacitor, C_b.
Given n_0, T_e, V_{rf} and C_b, calculate V_d, V_T and V_p.

Semi-analytic Model

- Having determined V_d, find ion energy distribution P(E).

$$P(E) = \frac{1}{2\pi} \left| \frac{dV_d}{d(\omega t)} \right|^{-1}_{E=eV_d}$$

A. Metze et al., *J. Appl. Phys*., **60**, 3081 (1986).
E. Kawamura et al., *Plasma Sources Science & Technology*, **8**, R45 (1999).

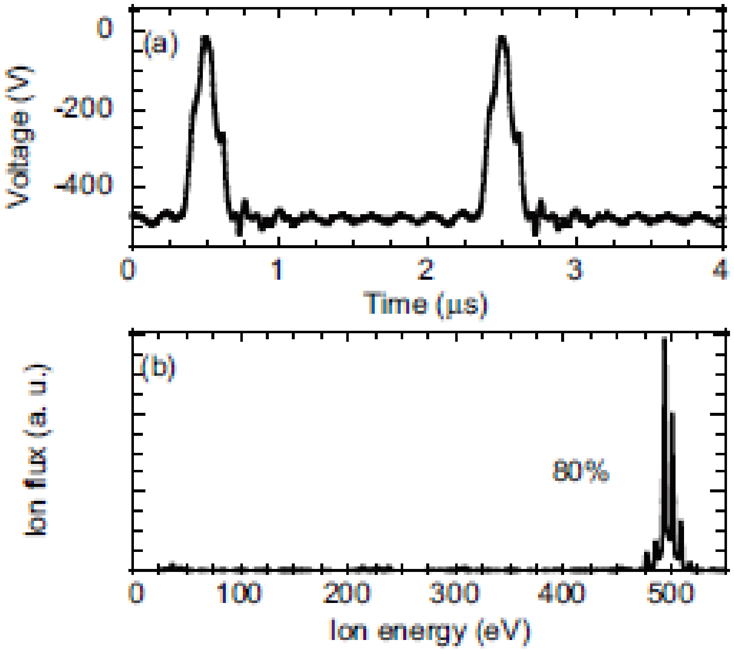
Tailored Voltage Waveforms

Apply a “tailored” voltage waveform (non-sinusoidal) on a target electrode so that the desired IEDF is obtained.

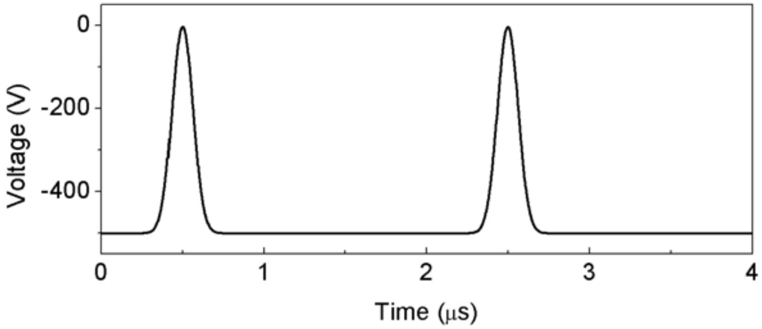
1. E. V. Barnat and T.-M. Lu, *J. Vac. Sci. Technol. A*, **17**, 3322 (1999).
2. S.-B. Wang and A. E. Wendt, *J. Appl. Phys*., **88**, 643 (2000).
3. E. V. Barnat and T.-M. Lu, *J. Appl. Phys*., **92**, 2984 (2002).
4. A. Agarwal and M. J. Kushner, *J. Vac. Sci. Technol. A*, **23**, 1440 (2005).
5. F. L. Buzzi, Y.-H. Ting and A. E. Wendt, *PSST*, **18**, 025009 (2009).
6. P. Kudlacek, R. F. Rumphorst, and M. C. M. van de Sanden, *J. Appl. Phys*., **106**, 073303 (2009).

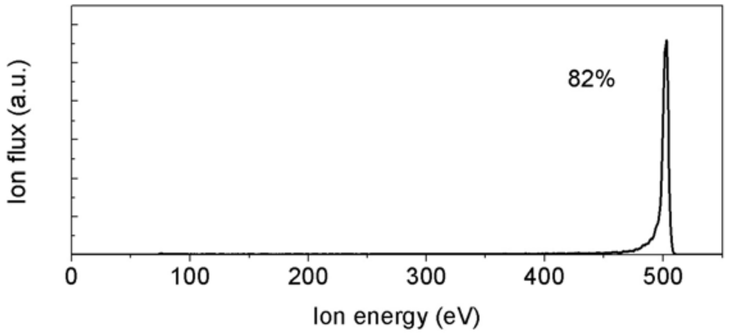
Tailored voltage waveforms: Spikes

Target voltage and Ar+ IEDF
F. L. Buzzi et al. *PSST*, **18** (2009) 025009



PIC simulation:
$n_e = 4\times10^{16}\ m^{-3}$, $T_e = 2eV$

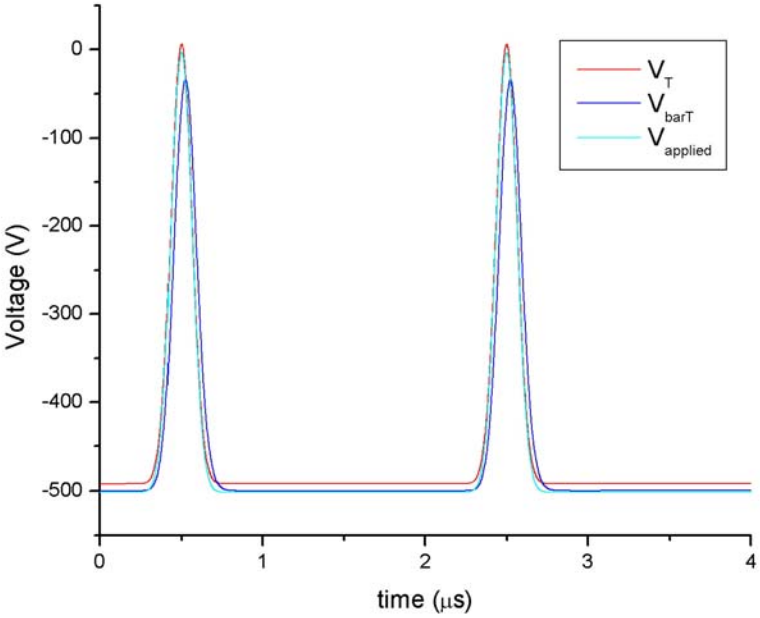


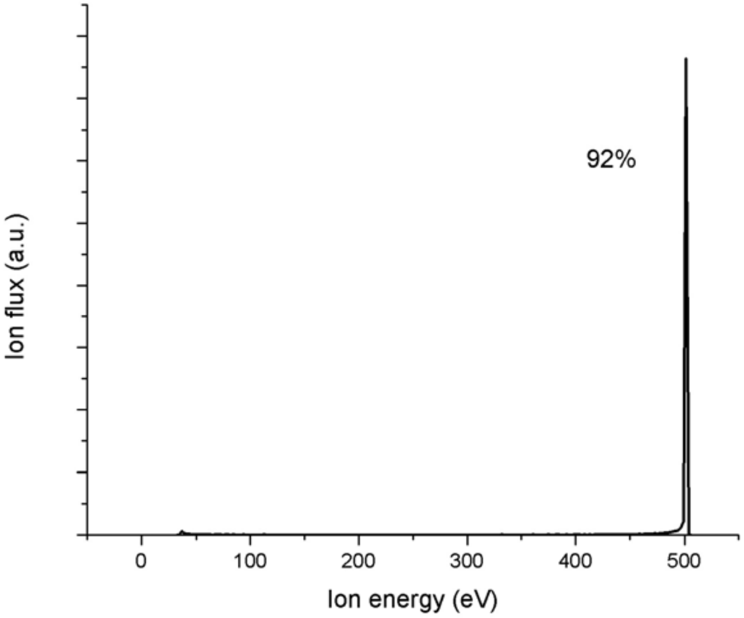


Tailored voltage waveforms: Spikes

Semi-analytical model:

$n_e = 4\times10^{16}\ \mathrm{m}^{-3}$, $T_e = 2$ eV, $C_B = 5\ \mu$F

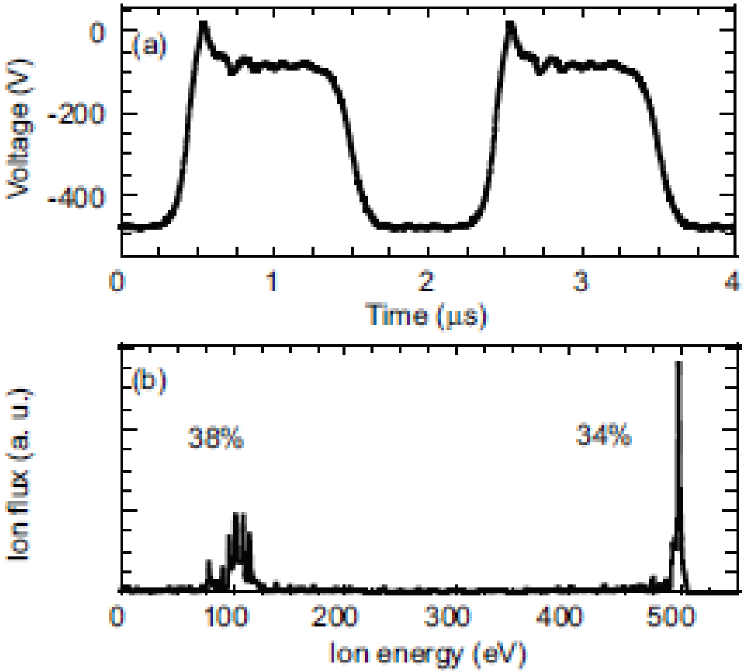




Tailored voltage waveforms: Staircase

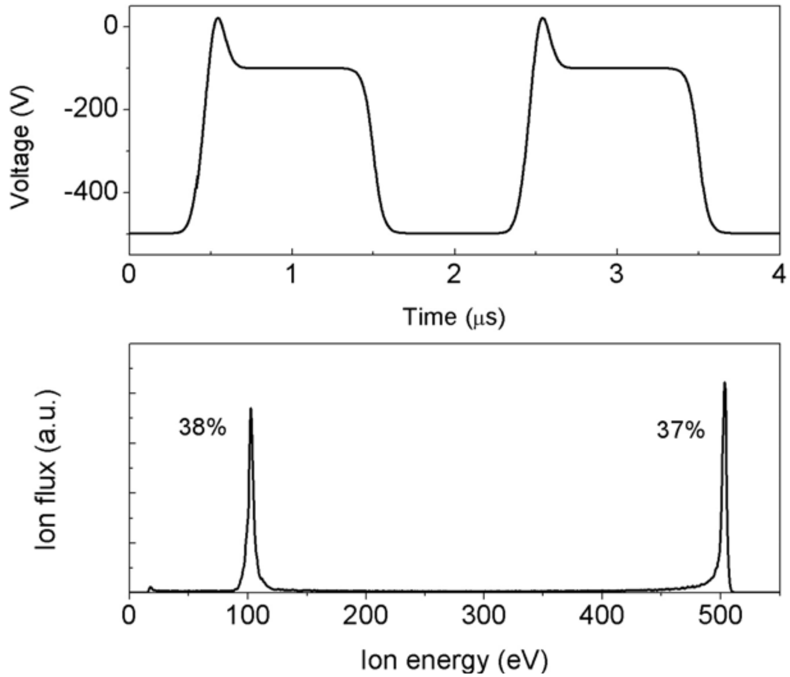
Target voltage and Ar+ IEDF

F. L. Buzzi et al. *PSST*, **18** (2009) 025009



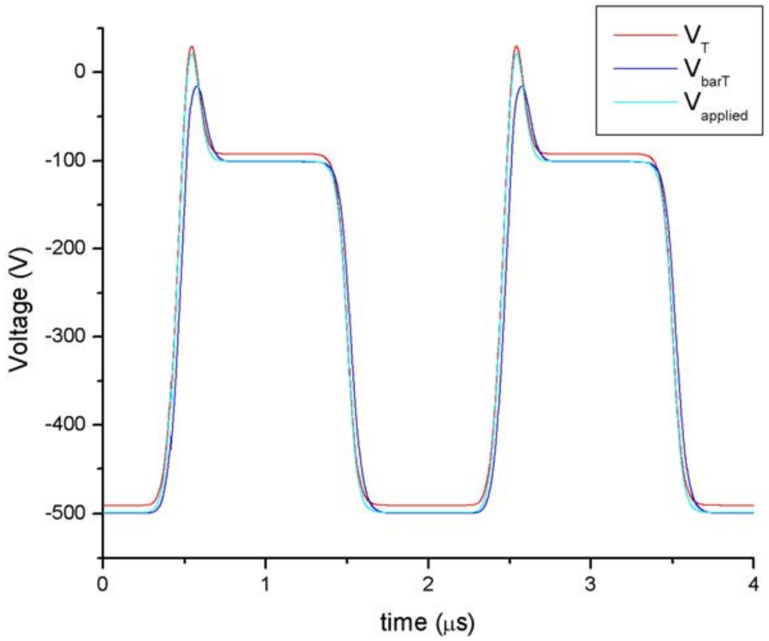
PIC simulation:

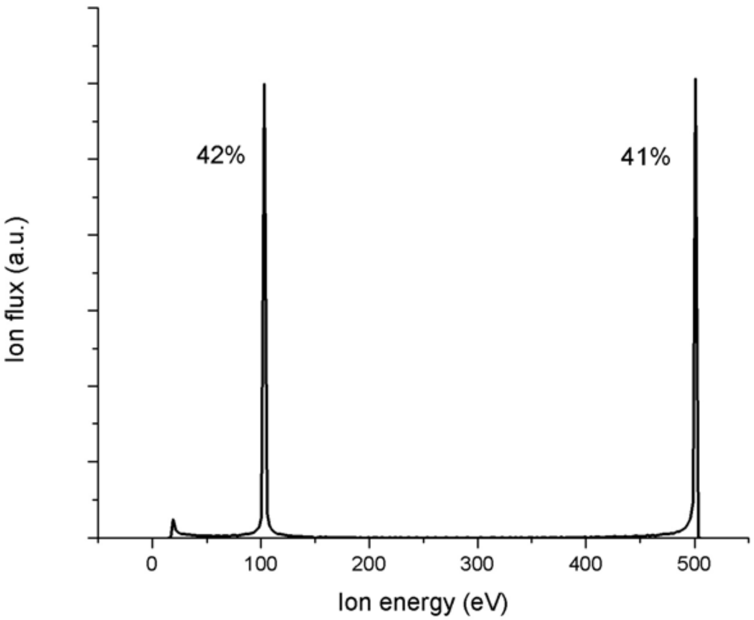
$n_e = 4\times10^{16}\ \mathrm{m}^{-3}$, $T_e = 2\mathrm{eV}$



Tailored voltage waveforms: Staircase

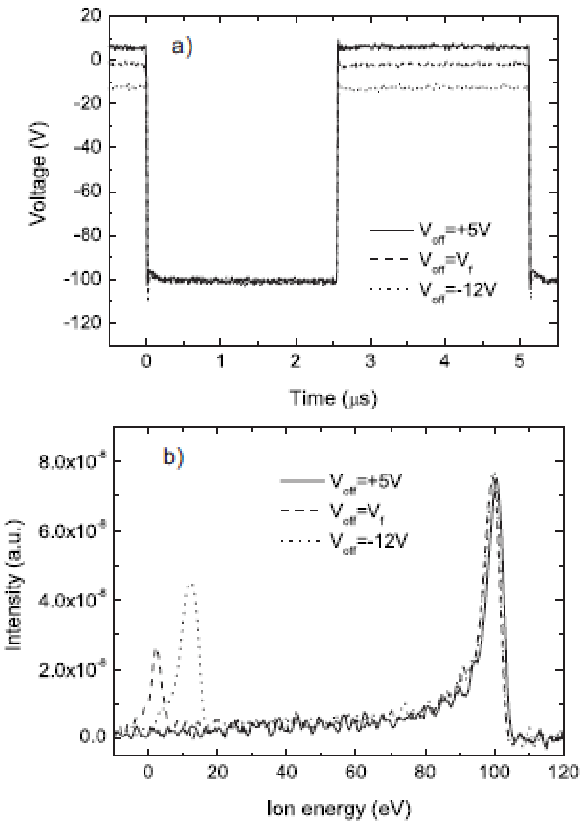
Semi-analytical model:
$n_e = 4\times10^{16}$ m^{-3}, $T_e = 2$ eV, $C_B = 5$ μF



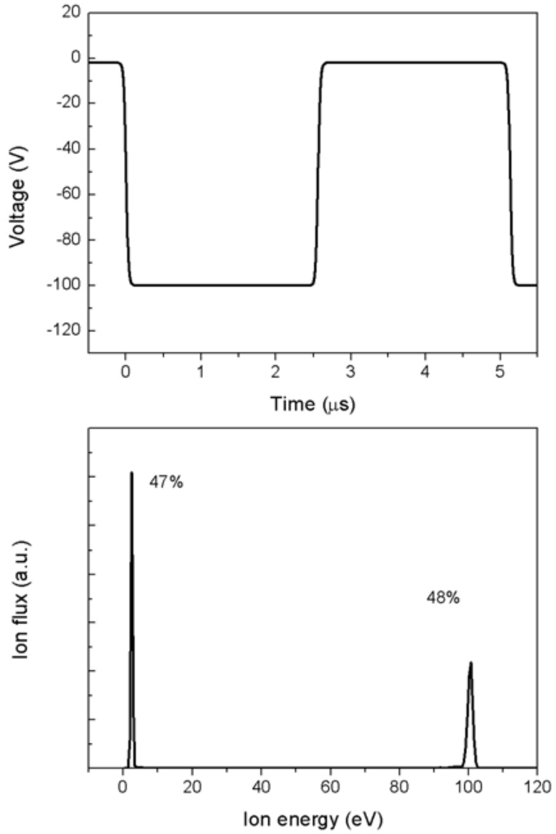


Tailored voltage waveforms: Square Wave (1)

Experiments (dashed line): H_3^+ ions
P.Kudlacek et al. *JAP* 106 (2009) 073303

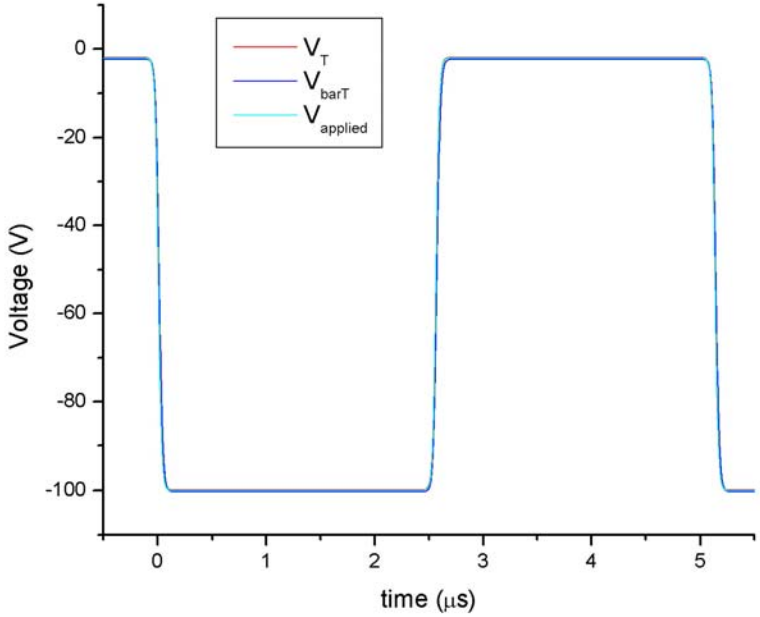


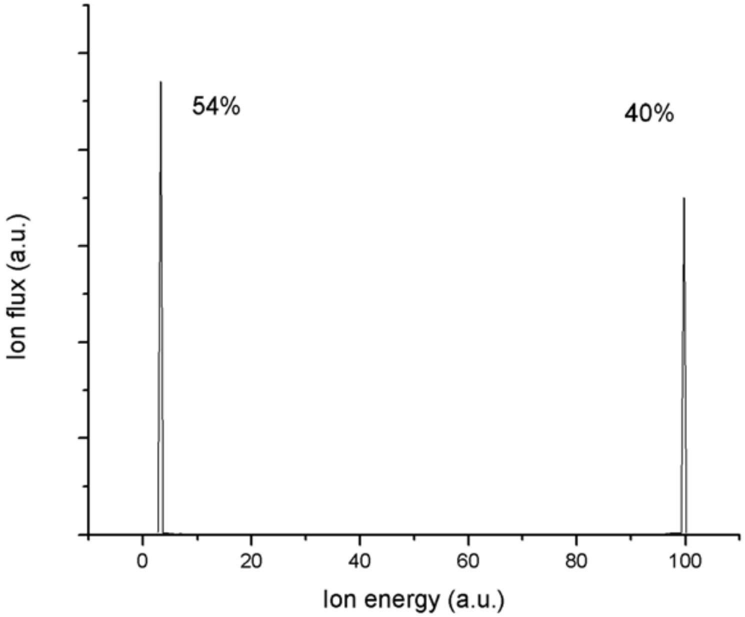
PIC simulation:
$n_e = 2\times10^{16}\ m^{-3}$, $T_e = 0.15$ eV



Tailored voltage waveforms: Square Wave (1)

Semi-analytical model:
$n_e = 2\times10^{16}\ \mathrm{m}^{-3}$, $T_e = 0.15$ eV, $C_B = 5\ \mu\mathrm{F}$

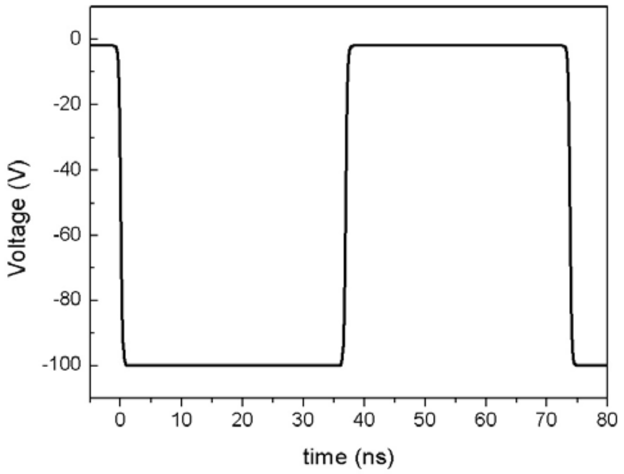


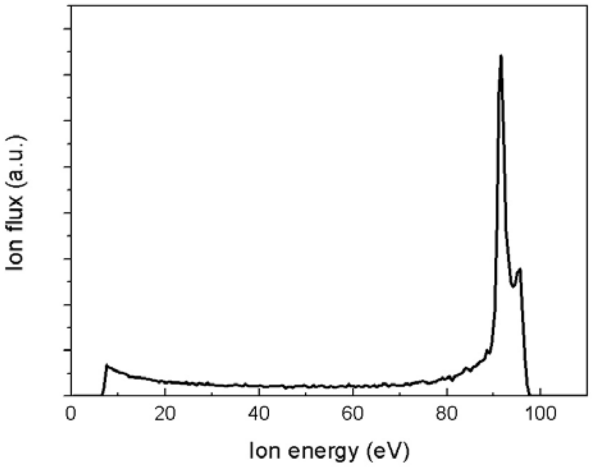


Tailored voltage waveforms: Square Wave (2)

PIC simulation:

$n_e = 2\times10^{16}\ \mathrm{m}^{-3}$, $T_e = 0.15$ eV, f = 13.56 MHz

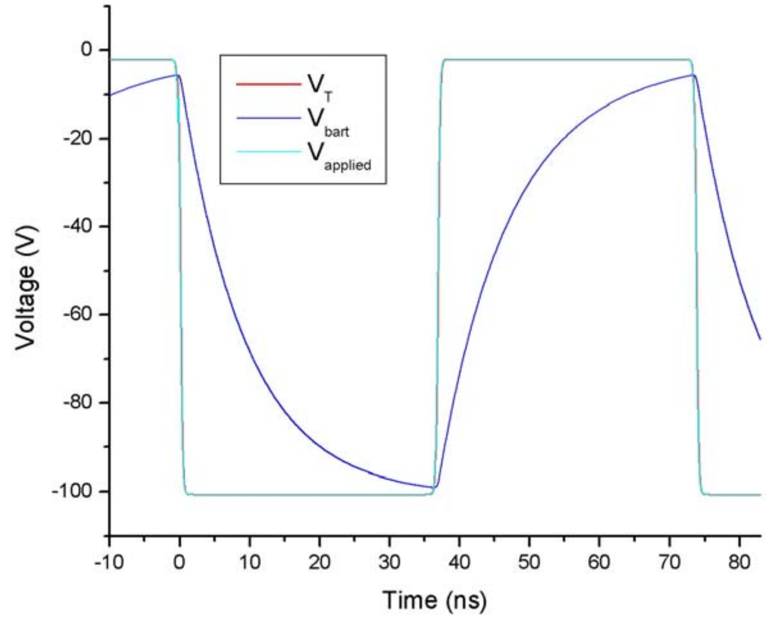


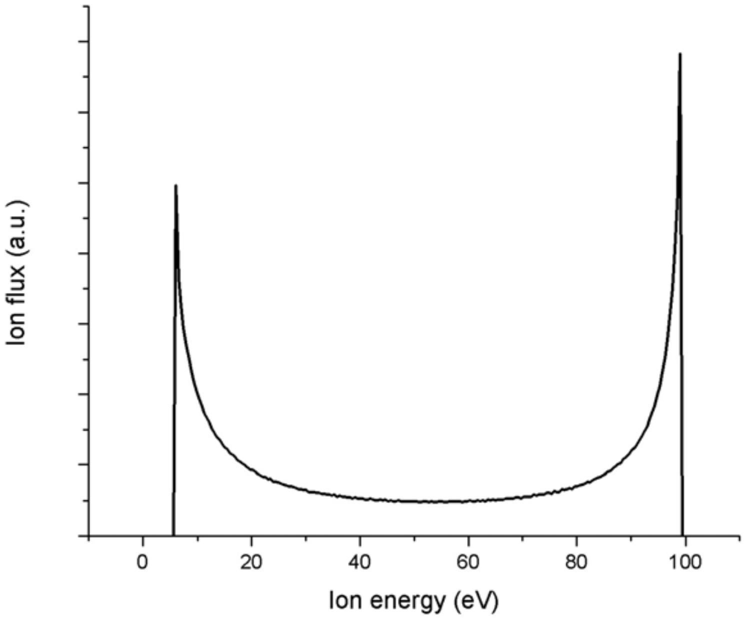


Tailored voltage waveforms: Square Wave (2)

Semi-analytical model:

$n_e = 2\times10^{16}\ \mathrm{m}^{-3}$, $T_e = 0.15$ eV, $C_B = 5\ \mu\mathrm{F}$





Summary & Future Work

- The energy distribution of ions bombarding the substrate can be tailored by applying voltage waveforms with special shapes (e.g., spikes, staircase, square wave).
- Semi-analytic model can rapidly identify voltage waveforms that can result in tailored IEDFs.
- PIC simulation is useful for verifying and fine tuning such waveforms, and for studying the effect of collisions.

Future Work: Apply modeling/simulation to UH experiments, study effect of collisions, attack inverse problem.