INFLUENCE OF ELECTRON-ELECTRON COLLISIONS ON ELECTRON ENERGY DISTRIBUTIONS AND TRANSPORT IN INDUCTIVELY COUPLED PLASMAS*

Alex V. Vasenkov and Mark J. Kushner
University of Illinois
Department of Electrical and Computer Engineering
Urbana, IL 61801

E-mail: vasenkov@uiuc.edu
mjk@uiuc.edu

URL: http://uigelz.ece.uiuc.edu

May 2002

*Work supported by CFD Research Corp., NSF, Applied Materials, Inc. and the SRC

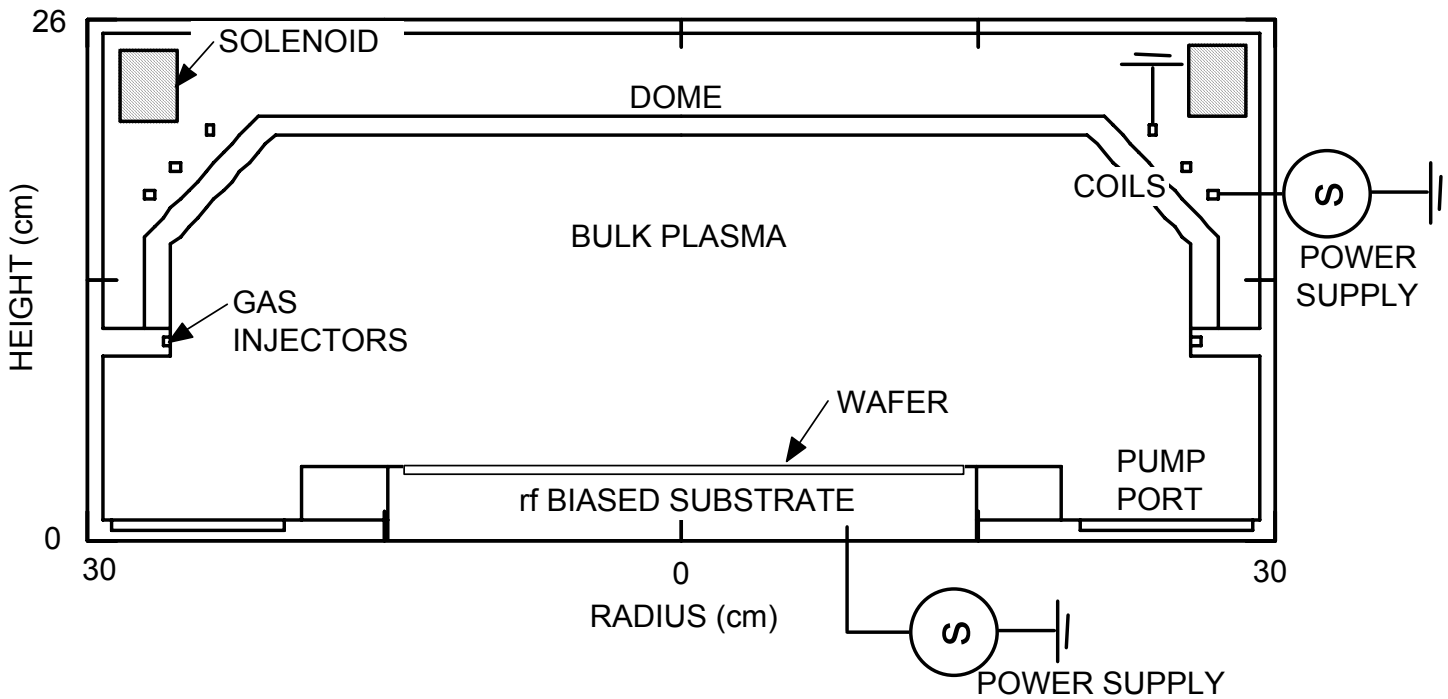
AGENDA

- Modeling of non-local electron kinetics in ICPs
- Description of the model
- Validation of the model for ICPs in Ar
- Stochastic heating in ICPs
- Modeling of electron transport for ICPs in CF_4
- Summary

University of Illinois
Optical and Discharge Physics

ELECTRON KINETICS IN ICPs

- **The trend towards using high-plasma density (>10^{11}cm^{-3}), low gas pressure (< 10s mTorr) sources in materials processing has resulted in renewed interest in electron kinetics in ICPs.**



- **Owing to the electron energy distribution (EED) is generally non-Maxwellian, a kinetic approach is required for modeling ICPs.**

ELECTRON KINETICS IN ICPs

- **One of the basic problems in the kinetic simulation of ICPs is the consideration of e-e collisions, which significantly influence the thermal motion of electrons.**

- **There are at least three approaches to resolve e-e collisions:**

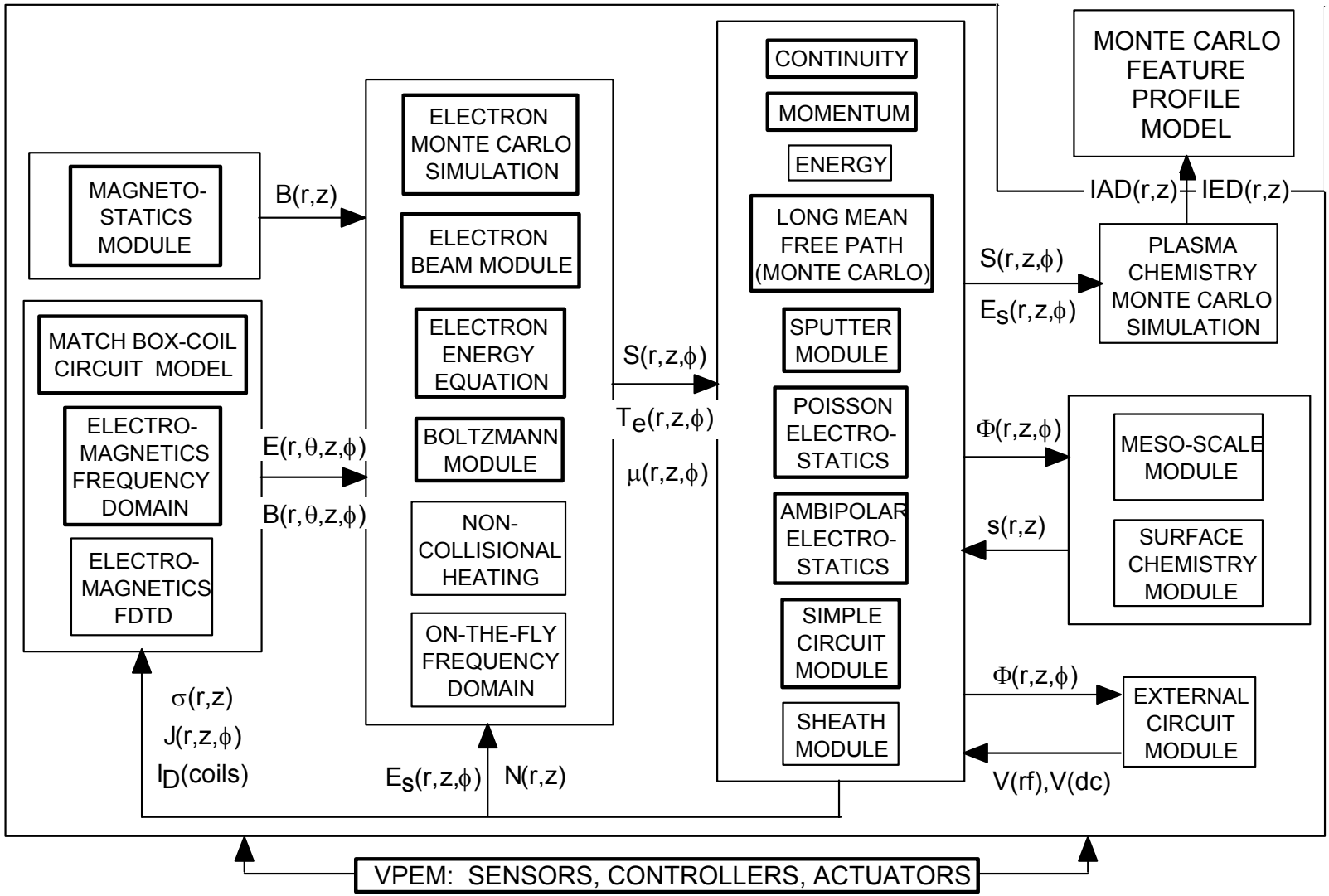
  (i) Particle-in-cell simulations (Nanbu *et al*, 1997, 2000)

  (ii) Direct solution of Boltzmann's equation (Kolobov *et al, 1997*)

  (iii) Electron Monte Carlo simulation (Weng *et al,* 1990)

University of Illinois
Optical and Discharge Physics

HYBRID PLASMA EQUIPMENT MODEL



University of Illinois
Optical and Discharge Physics

ALGORITHM FOR E-E COLLISIONS

- The basis of the algorithm for e-e collisions is “particle-mesh”.
- Statistics on the EEDs are collected according to spatial location.
- An energy of collision target is randomly selected from the EED at this location

$$P(\varepsilon_{tr}) = f(\varepsilon_{tr})\sqrt{\varepsilon_{tr}}\,\Delta\varepsilon_{tr}\Delta t \Big/ \left(\sum_i f(\varepsilon_i)\sqrt{\varepsilon_i}\,\Delta\varepsilon_i \Delta t_i \right)$$

- Since, the number of energy bins is usually large (400-500), quick lookup techniques are used for the energy of collision targets.
- In this technique the l*th* cumulative probability is determined from

$$\Pi_l = \sum_{\varepsilon'_{l-1} \le \varepsilon_j \le \varepsilon'_l} P(\varepsilon_j) \Big/ \sum_i P(\varepsilon_i)$$

University of Illinois
Optical and Discharge Physics

ALGORITHM FOR E-E COLLISIONS

- **The energy of the collision partner is first randomly selected on a coarse basis, followed by a refinement within the large energy intervals.**
- **Assuming an isotropic velocity for the target, the probability for an e-e collision is determined using the relative speed between the electron and its target,**

$$P_{ee} = n_e(\vec{r}) \cdot \sigma_{ee}(g) \cdot g \cdot \Delta t, \;\; g = \left| \vec{v}_{pr} - \vec{v}_{tr} \right|$$

$$\sigma_{ee}(g) = 4\pi b_o^2(g) \left[1 + \ln\left(\frac{\lambda_D}{b_o(g)} \right) \right], \;\; b_o(g) = \frac{q^2 / 4\pi\varepsilon_o}{\frac{1}{2} m_e g^2}$$

University of Illinois
Optical and Discharge Physics

ALGORITHM FOR E-E COLLISIONS

- **If a collision occurs, then a post collision relative velocity is randomly determined as,**

$$g_z' = \pm|\vec{g}|r_1, \qquad g_x' = |\vec{g}|\sqrt{1-r_1^2}\cos(2\pi r_2)$$

$$g_y' = |\vec{g}|\sqrt{1-r_1^2}\sin(2\pi r_2)$$

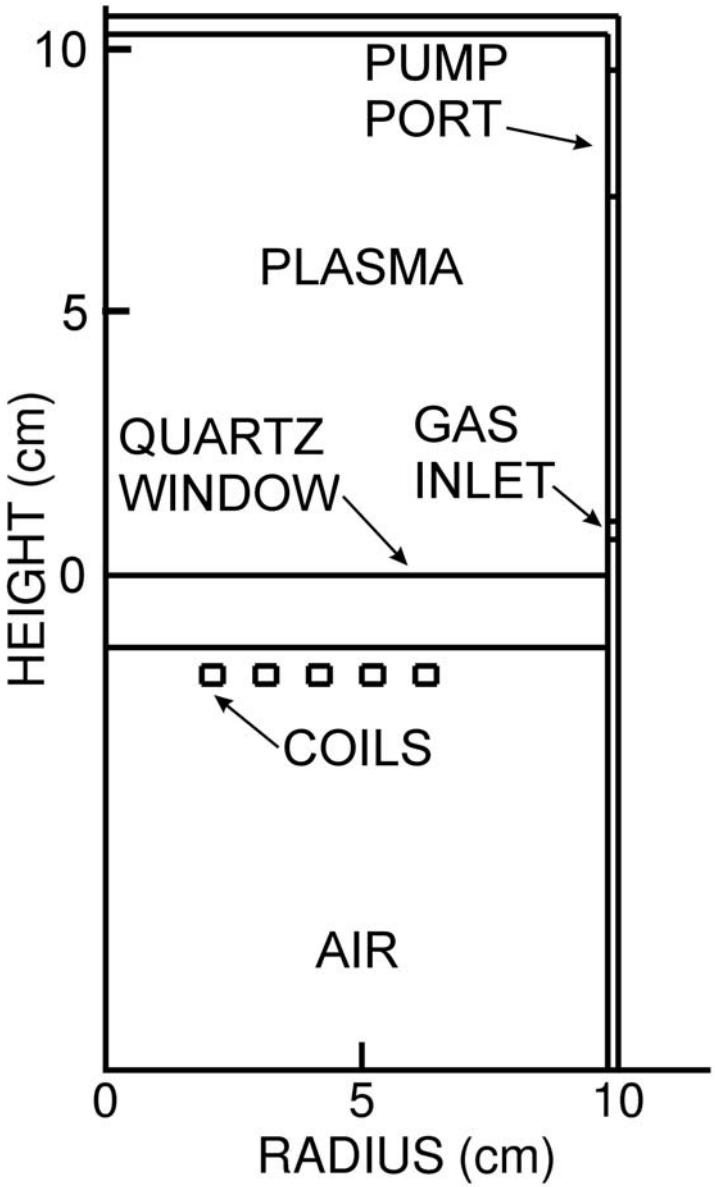
- **Finally, the velocity of the pseudo-electron is updated with,**

$$\vec{v}_f = \vec{v}_R + 0.5\vec{g}' \qquad \vec{v}_R = 0.5(\vec{v}_{tr} + \vec{v}_{pr})$$

- **The change in velocity of the collision partner is disregarded; e-e collisions are treated as collisions between pseudo-electrons and energy resolved electron fluid.**
- **The consequences of e-e collisions on the targets are obtained by continuously updating the stored EEDs.**

University of Illinois
Optical and Discharge Physics

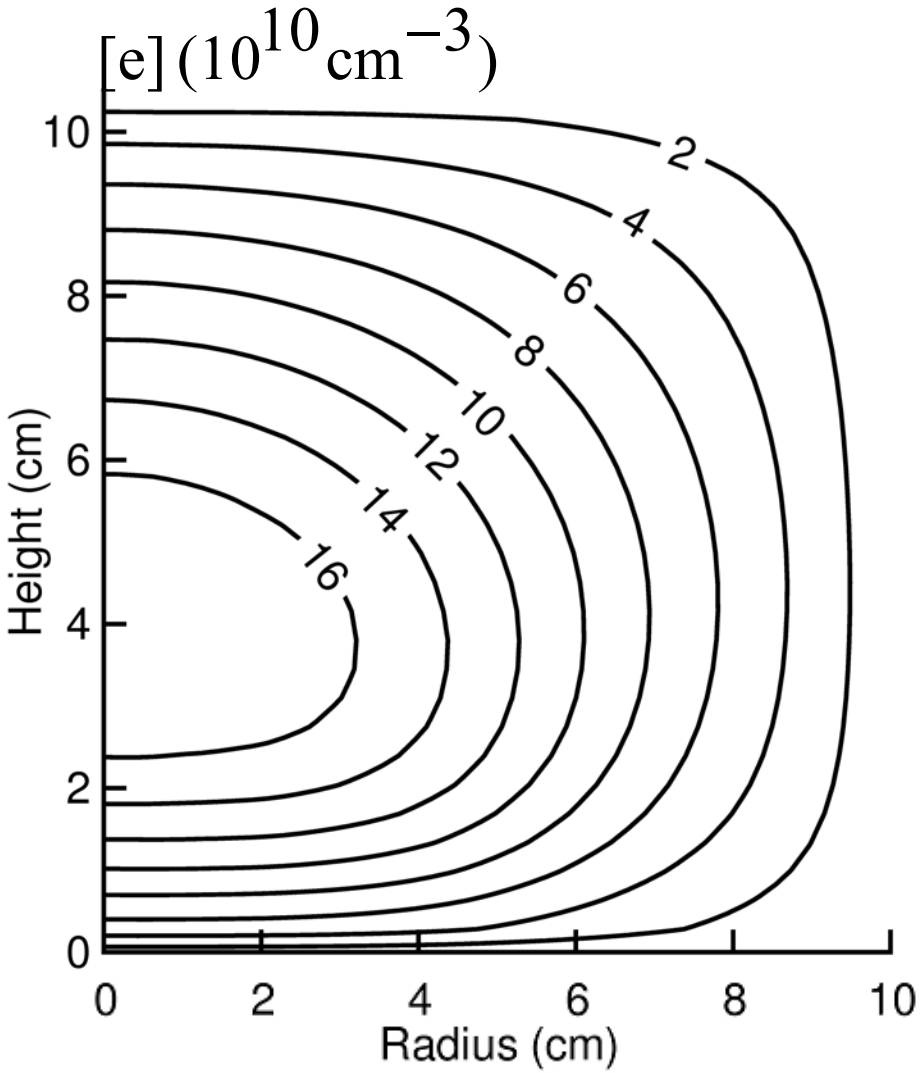
ICP CELL FOR VALIDATION AND INVESTIGATION



- **Experiments by Godyak *et al* (1998) are used for validation.**
- **The experimental cell is an ICP reactor with a Faraday shield to minimize capacitive coupling.**

University of Illinois
Optical and Discharge Physics

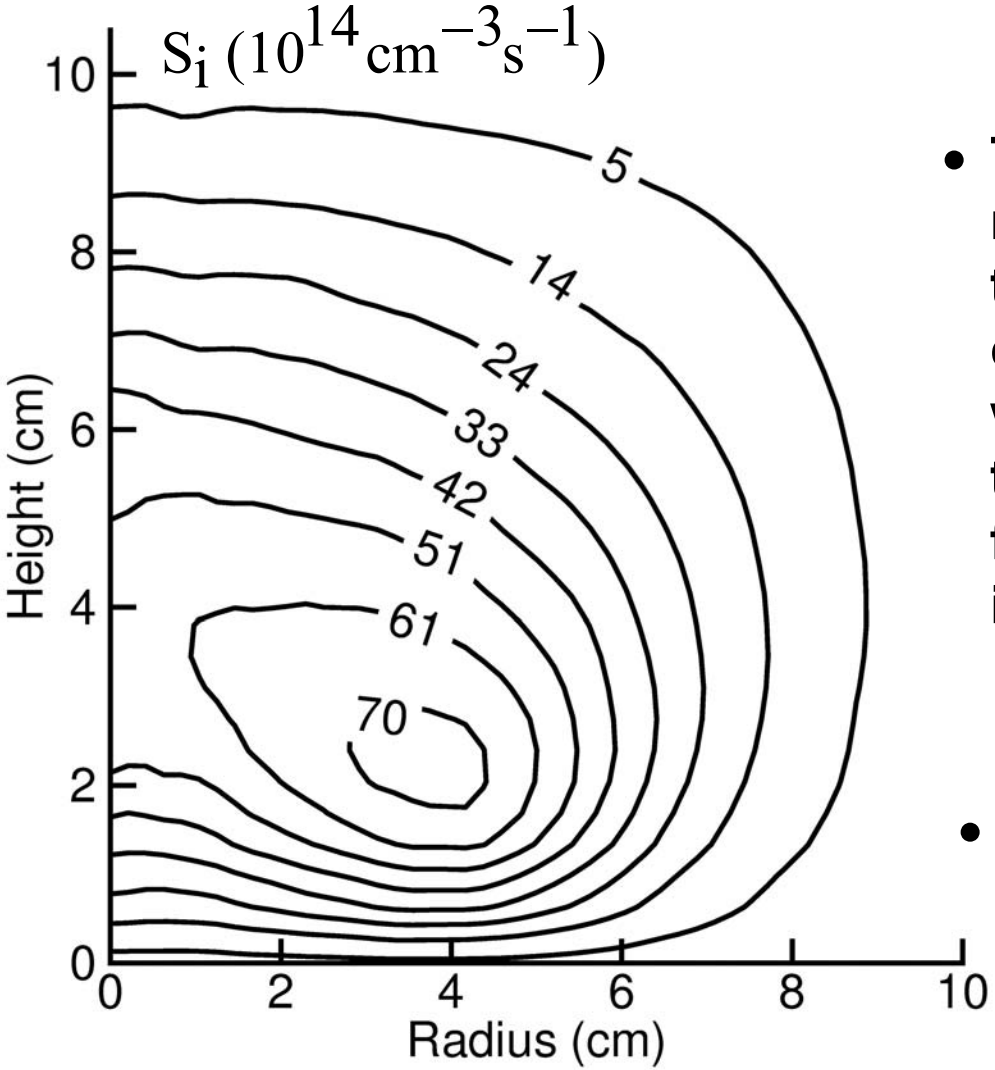
ELECTRON DENSITY FOR STANDARD CASE



- **Electron density is largest in the middle of reactor where the electric potential is maximum.**
- **Ar, 10 mTorr, 100 W, 6.78 MHz**

University of Illinois
Optical and Discharge Physics

IONIZATION SOURCE FOR STANDARD CASE

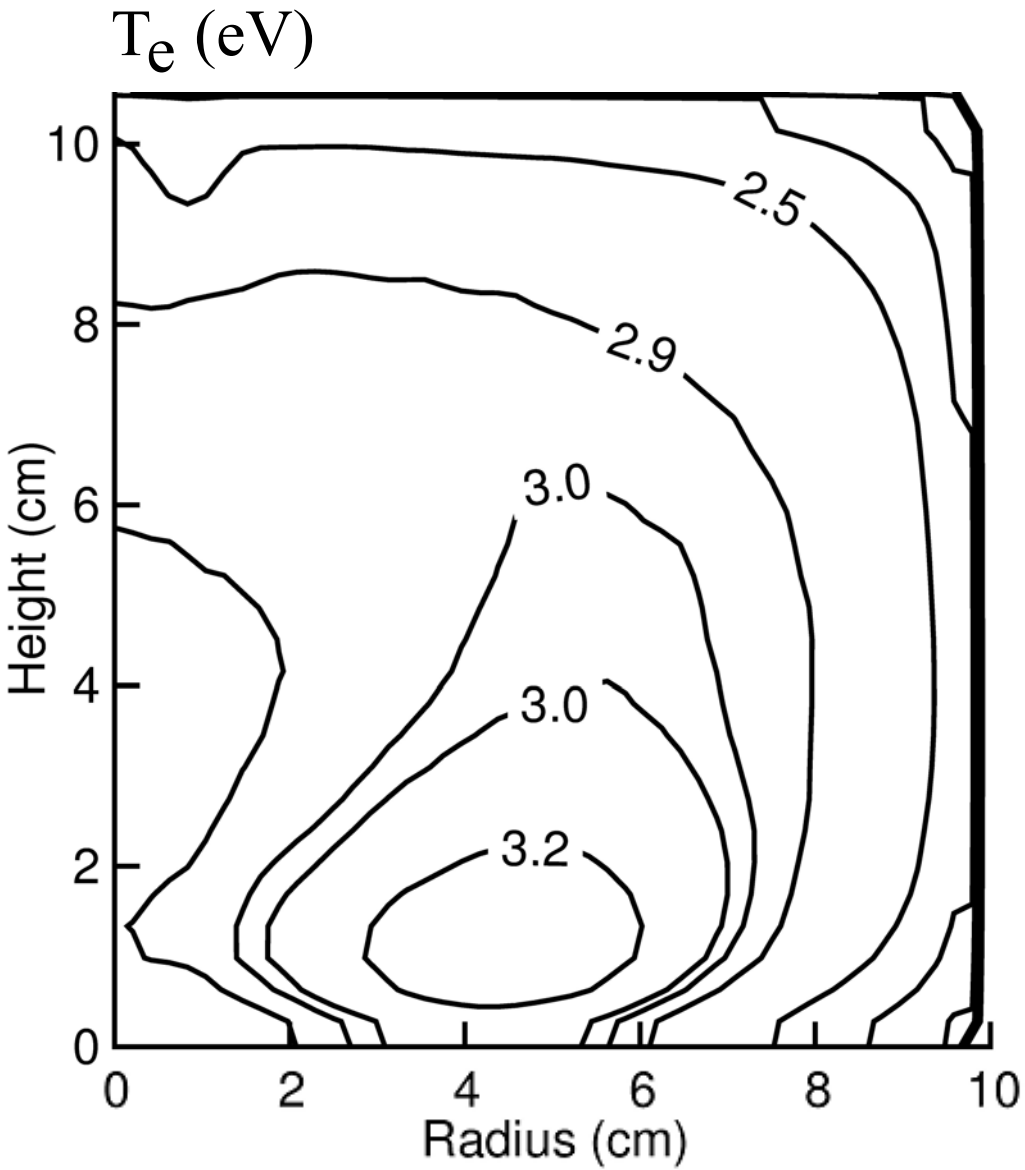


- **The ionization source reaches a maximum at the edge of the classical skin depth where the amplitude of the electromagnetic field decays to 1/e of its edge value.**

- **Ar, 10 mTorr, 100 W, 6.78 MHz**

University of Illinois
Optical and Discharge Physics

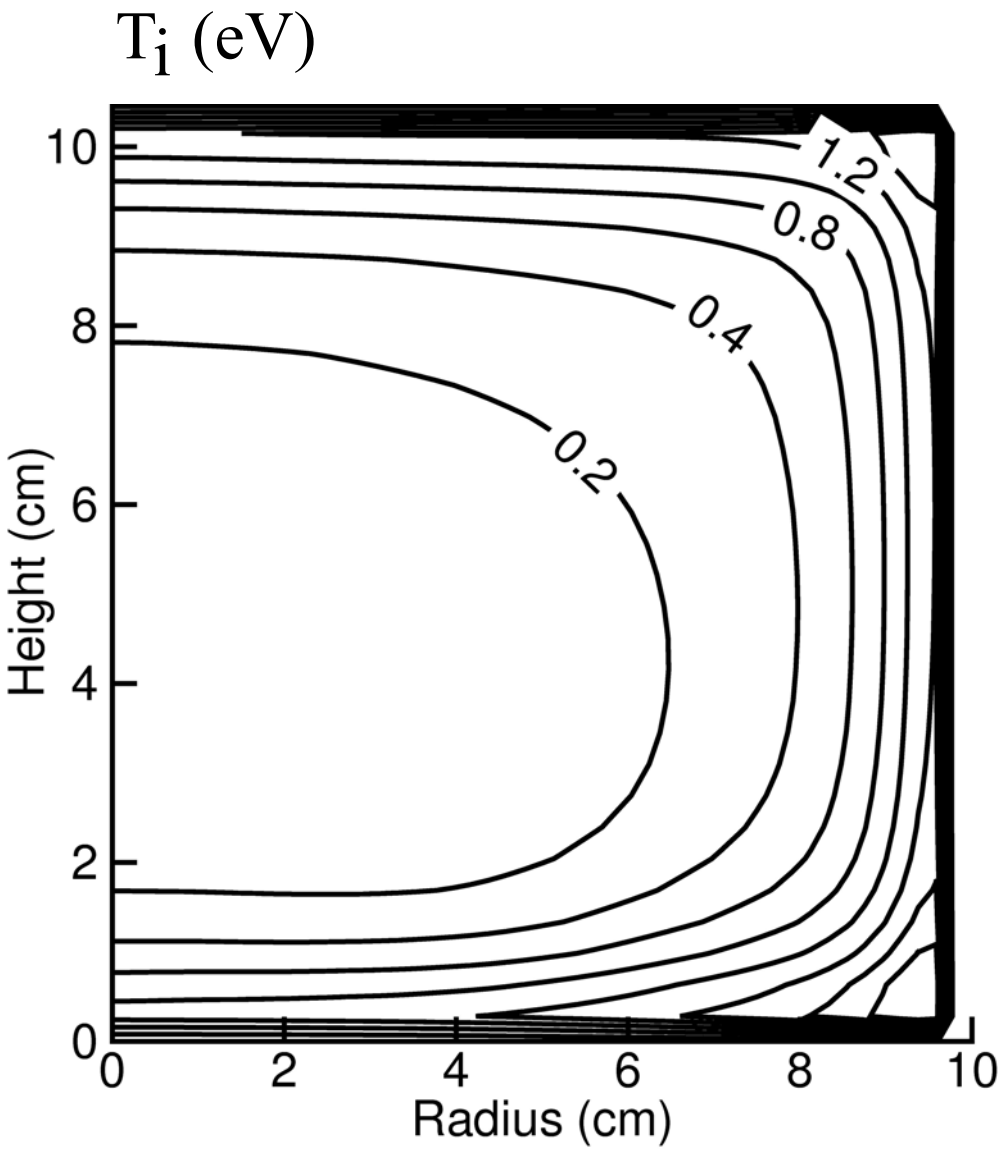
T_e FOR STANDARD CASE: Ar, 10 mTorr, 100 W, 6.78 MHz



- **The first major peak occurs in the skin depth owing to collisionless electron heating by the large electric field.**
- **The second minor peak corresponds to the position where the electron density reaches the maximum.**

University of Illinois
Optical and Discharge Physics

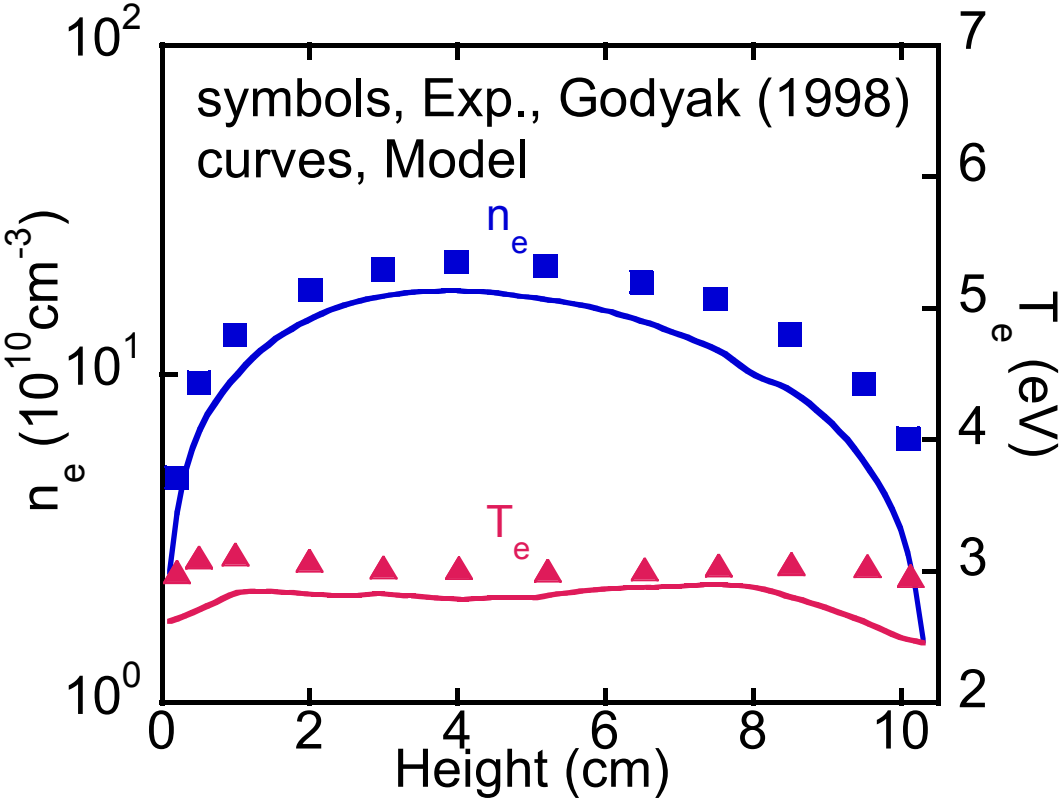
T_i FOR STANDARD CASE: Ar, 10 mTorr, 100 W, 6.78 MHz



- The ion temperature reaches a maximum near the walls where ions gain energy due to acceleration in the presheath.
- In the middle of reactor the ion temperature is lower owing to thermalization with neutral species.

University of Illinois
Optical and Discharge Physics

T_e and n_e ALONG THE CENTERLINE OF THE REACTOR

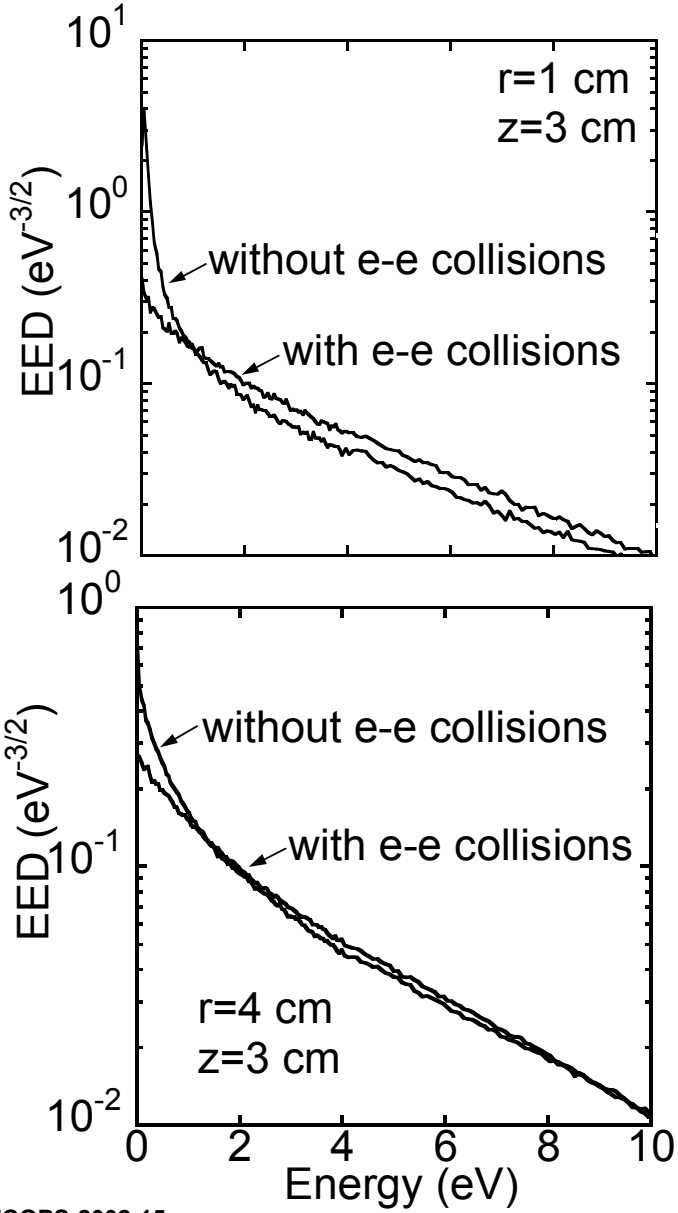


- **The maximum of electron density is displaced from the center due to the axial location of the source function.**
- **The high thermal conductivity and redistribution of energy by e-e collisions produce nearly uniform electron temperatures.**

- **Ar, 10 mTorr, 100 W, 6.78 MHz, r=0**

University of Illinois
Optical and Discharge Physics

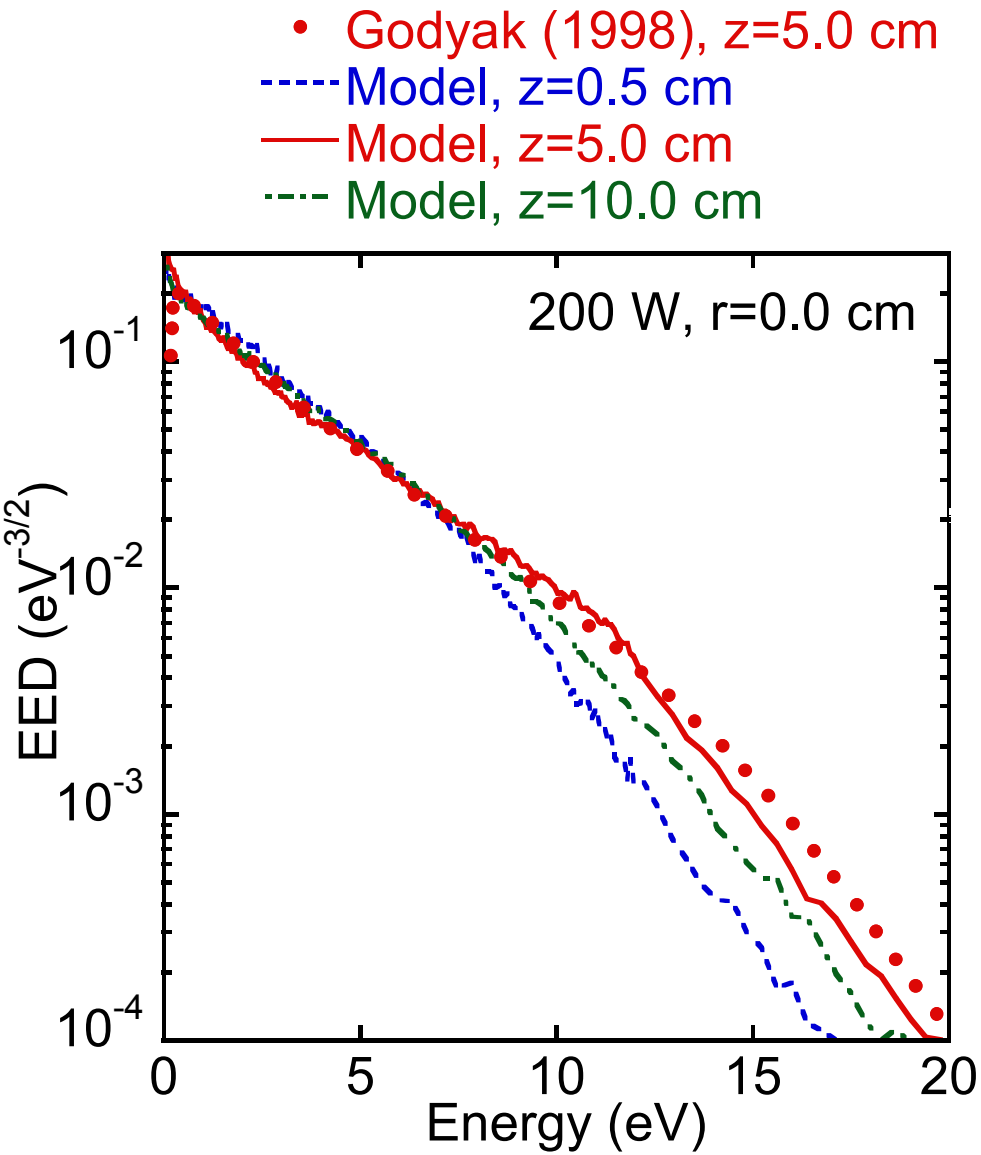
EFFECT OF E-E COLLISIONS ON THE EEDs



- **Low energy electrons want to "pool" at the peak in plasma potential in the center of the reactor.**
- **When including e-e collisions, the fraction of low-energy electrons is smaller due to energy transfer between low-energy and high-energy electrons.**
- **Ar, 10 mTorr, 100 W, 6.78 MHz**

University of Illinois
Optical and Discharge Physics

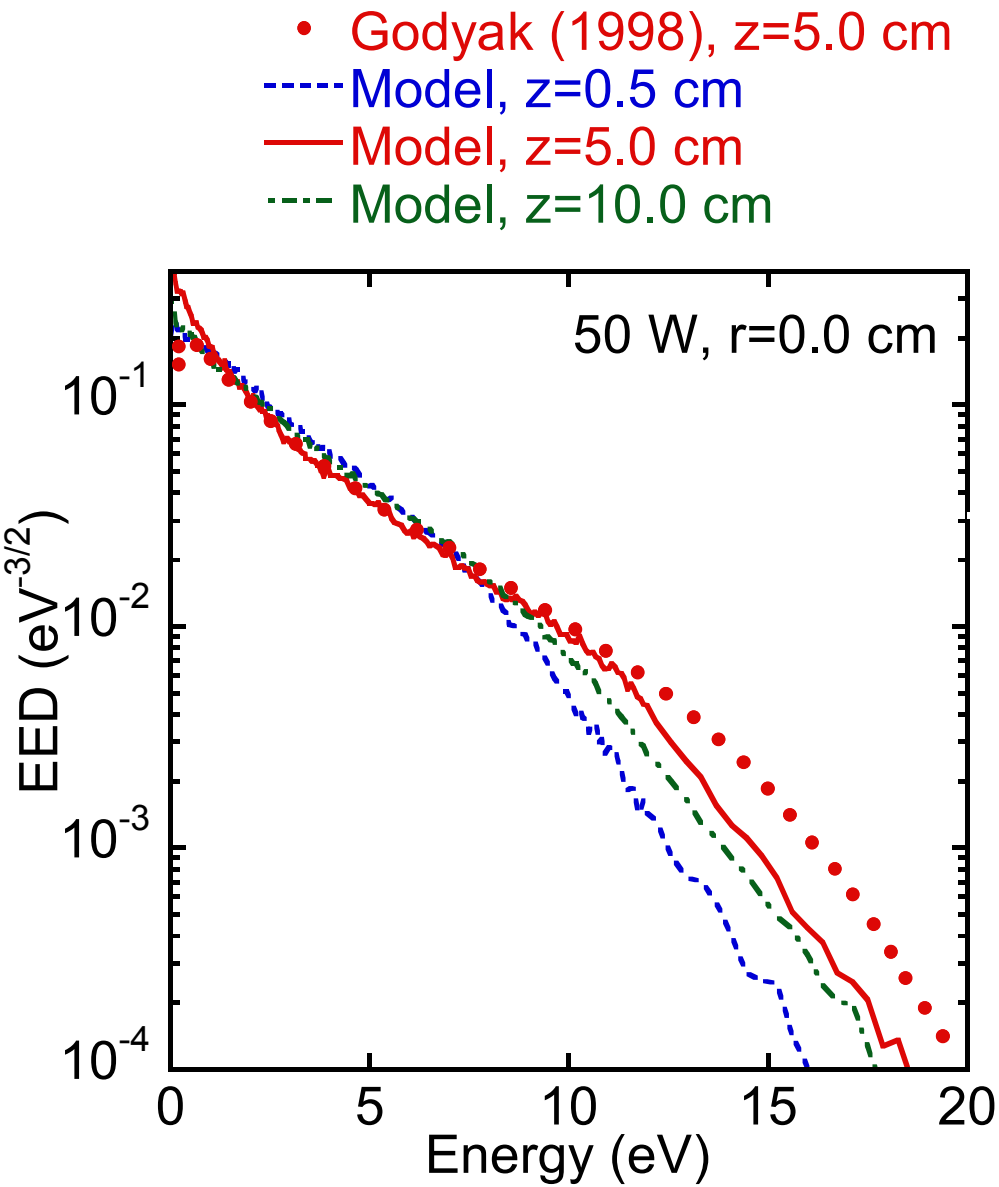
EEDs ALONG THE CENTERLINE OF THE REACTOR



- **Ar, 10 mTorr, 6.78 MHz**
- **The EEDs show a bi-Maxwellian distribution, which is typical for low-pressure inductively coupled plasmas.**
- **The EED in the middle of the reactor has the largest energy tail**

University of Illinois
Optical and Discharge Physics

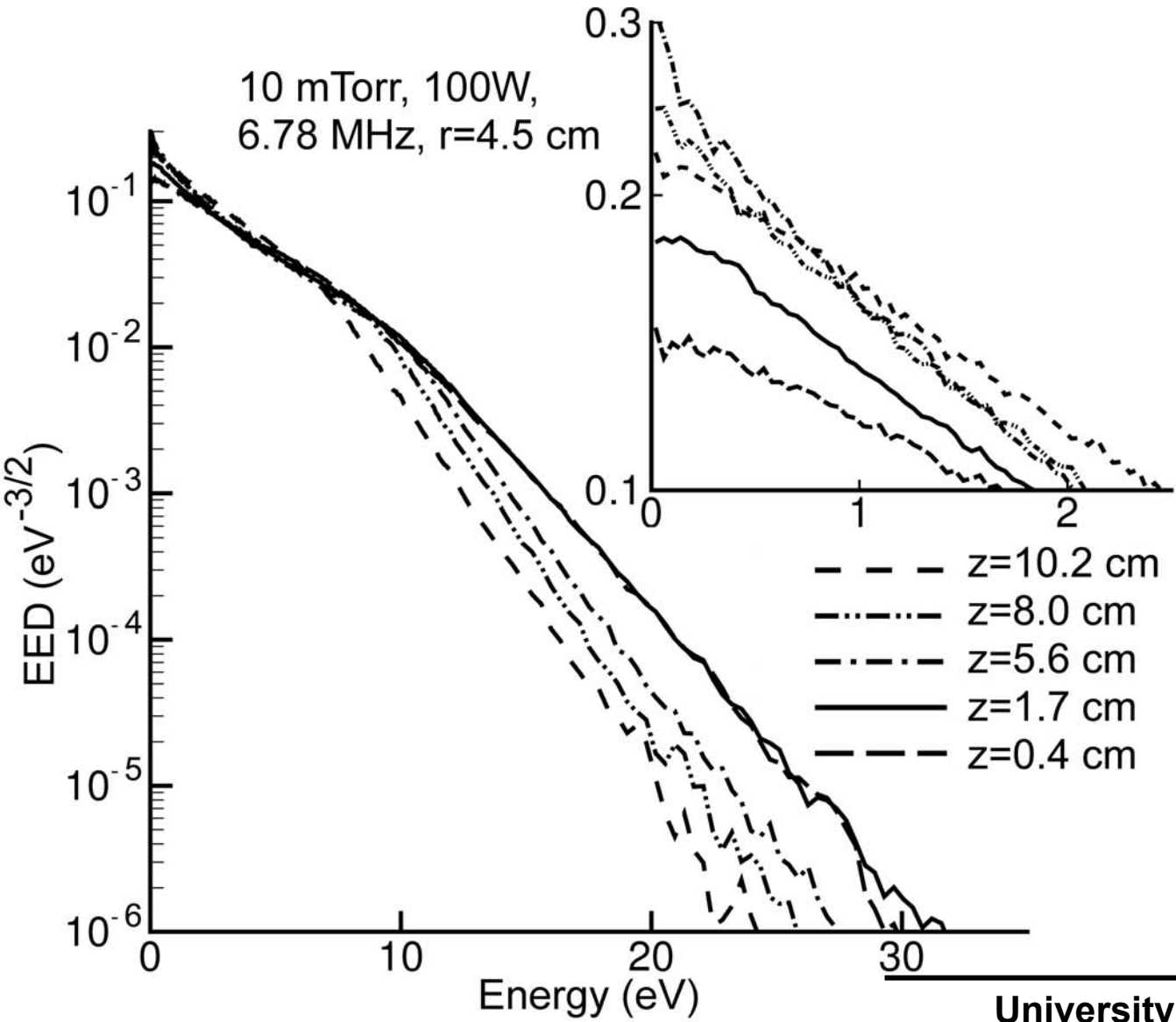
EEDs ALONG THE CENTERLINE OF THE REACTOR



- **Ar, 10 mTorr, 6.78 MHz**
- **In the skin layer the EED is depleted at low energies.**
- **EEDs near the peak plasma potential (z = 5.0 cm) have larger a low energy component.**

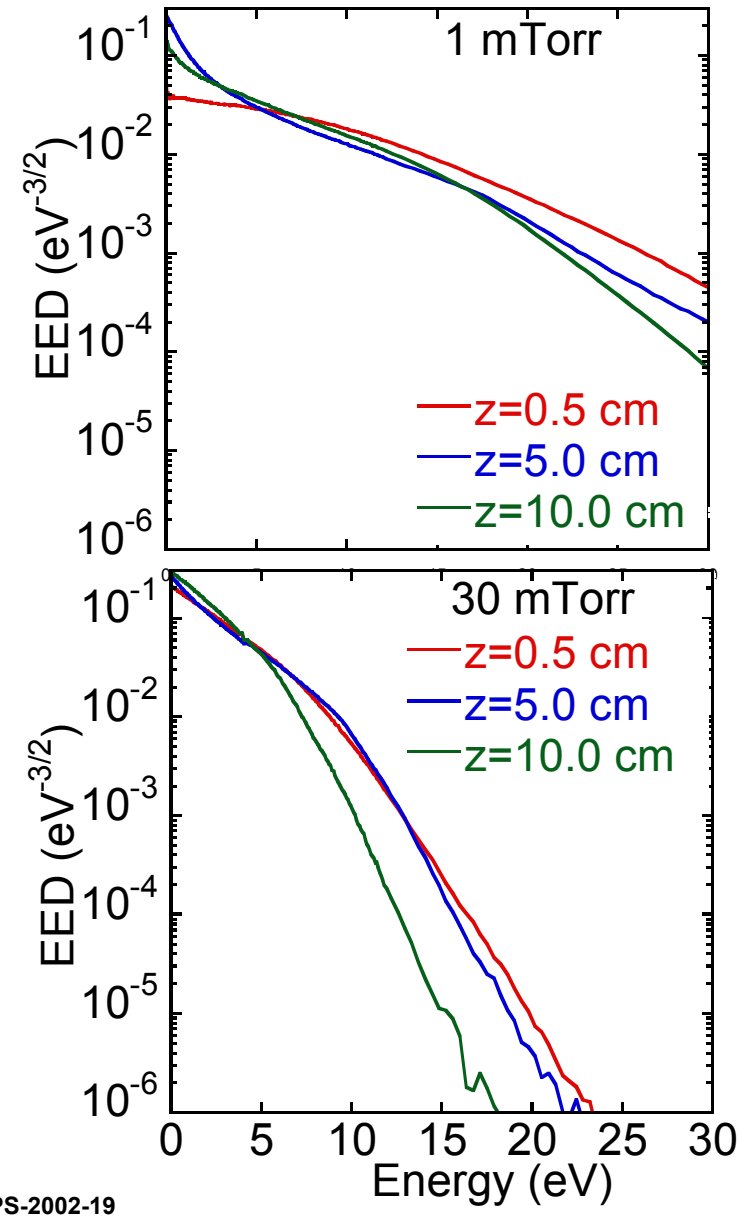
University of Illinois
Optical and Discharge Physics

EEDs IN SKIN LAYER AND BULK PLASMA



University of Illinois
Optical and Discharge Physics

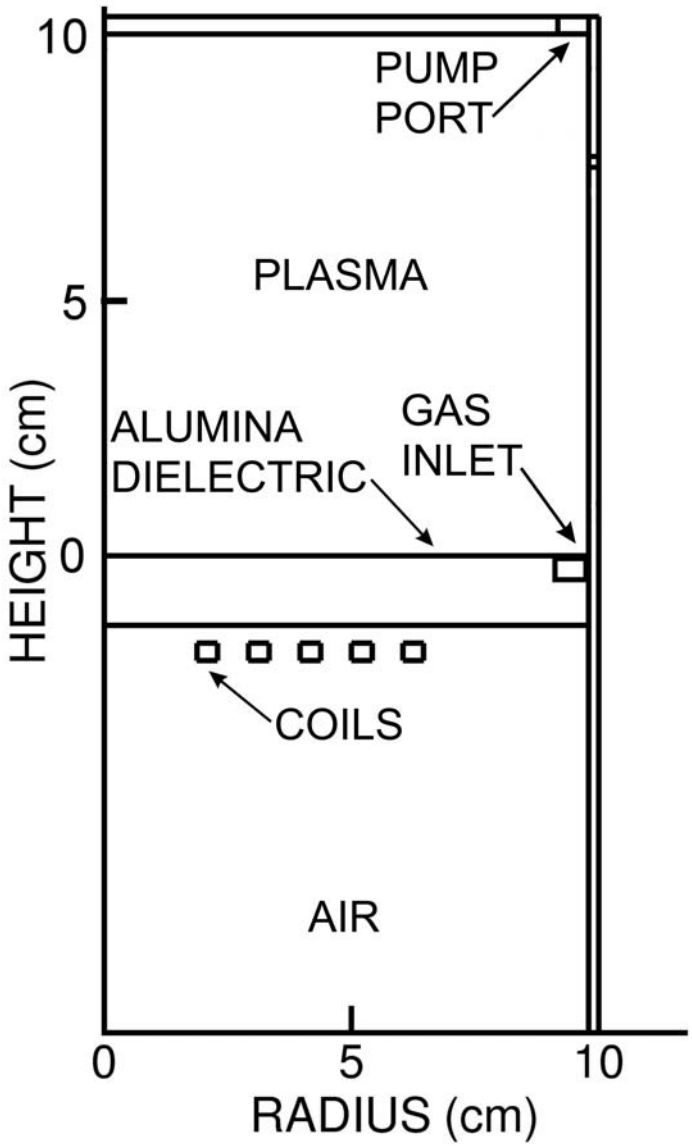
EFFECT OF PRESSURE ON THE EEDs



- Ar, 100 W, 6.78 MHz
- At 1 mTorr the EEDs are dominated by collisionless heating and by non-linear Lorentz forces, which provide an axial acceleration.
- The EEDs at 30 mTorr are in a collisional regime and therefore they resemble a Druyvesteyn distribution.

University of Illinois
Optical and Discharge Physics

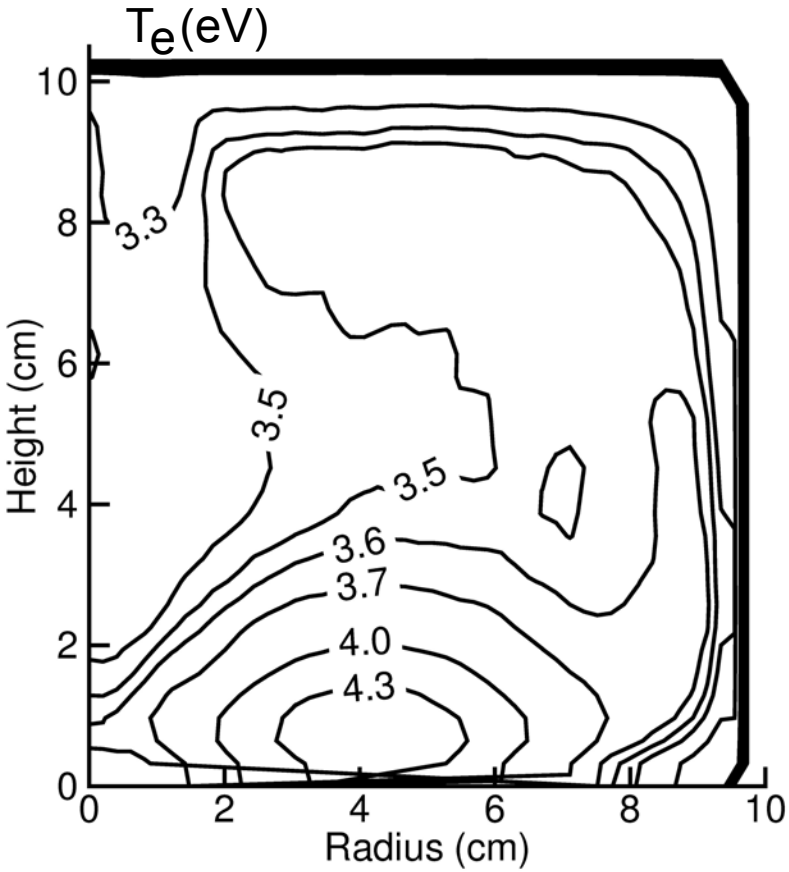
EXPERIMENTAL CELL FOR INVESTIGATION OF ICPs IN CF_4

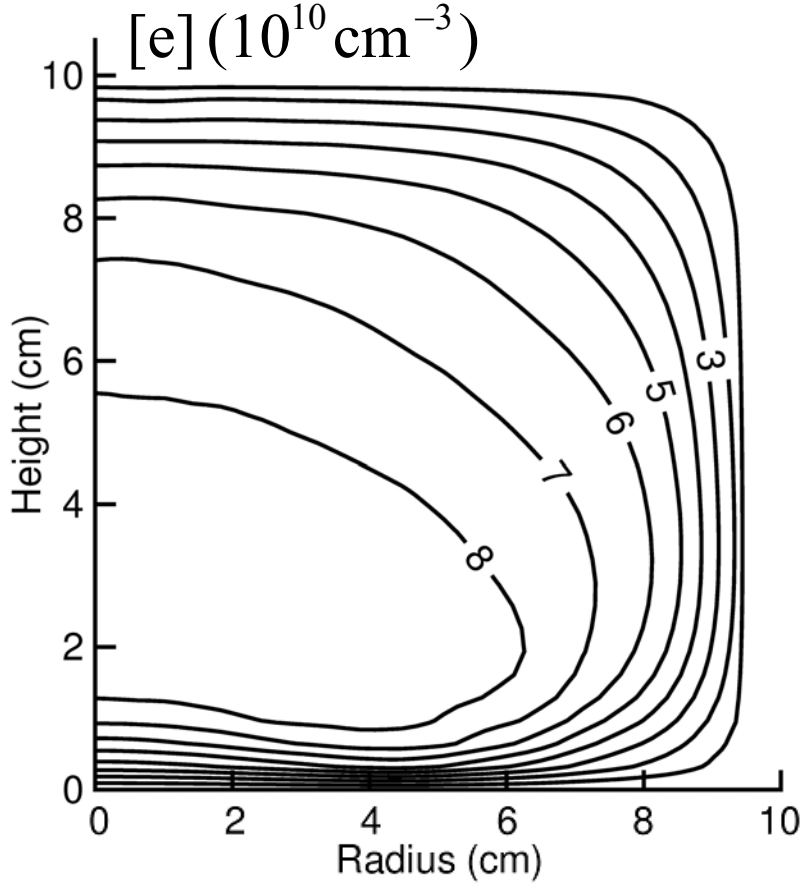


- **Modeling of ICPs in CF_4 involves complex surface and gas-phase chemistry.**
- **It is particularly challenging due to only limited data is available for electron–CF_x and CF_x-CF_x radical collisions.**
- **Experiments by Singh, Coburn, and Graves [J. Vac. Sci. Technol. A v. 19, 718 (2001)] are used for a comparison.**

University of Illinois
Optical and Discharge Physics

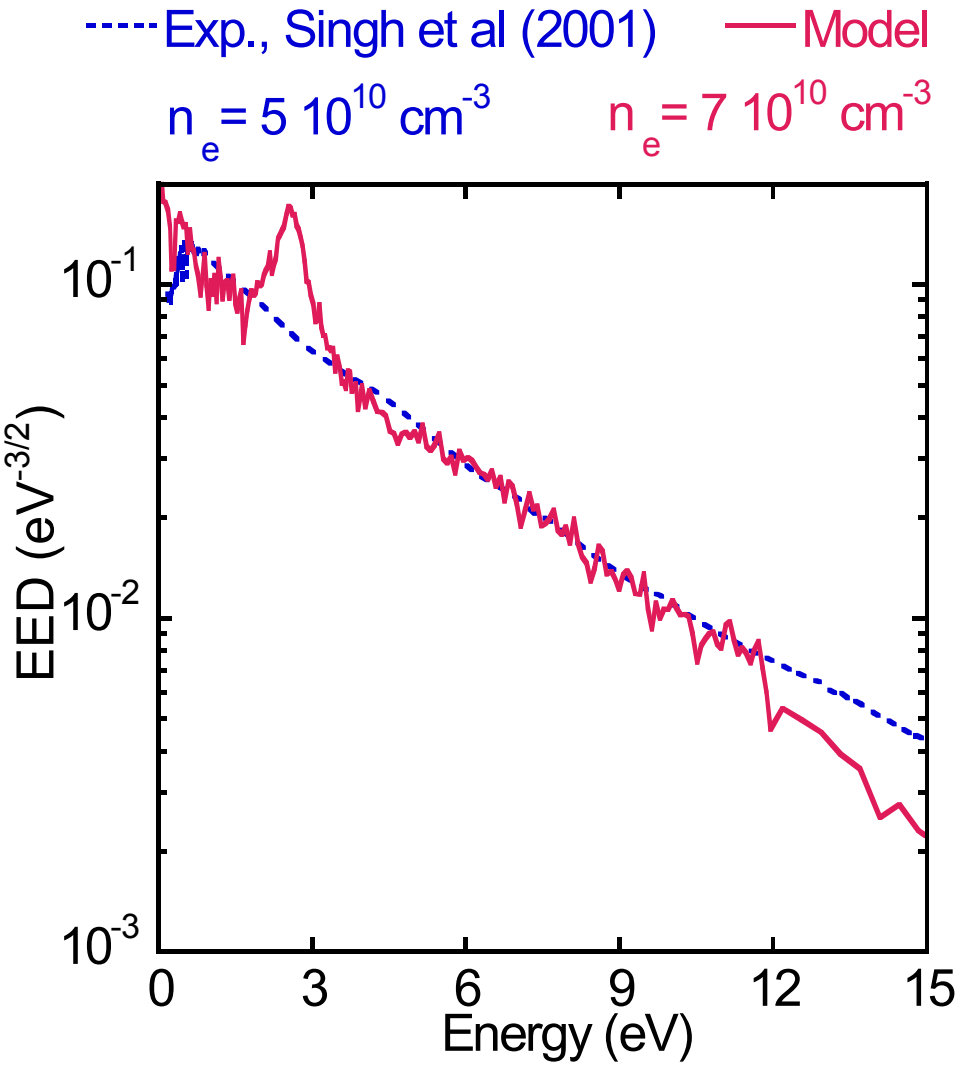
T_e, n_e for CF_4, 10 mTorr, 150 W, 13.56 MHz





- **Electron temperature in CF_4 shows similar features to that in Ar, but it is higher in magnitude due to the dissociation.**
- **The region of largest electron density intersects with the skin layer.**

EXPERIMENTAL AND COMPUTED EEDs

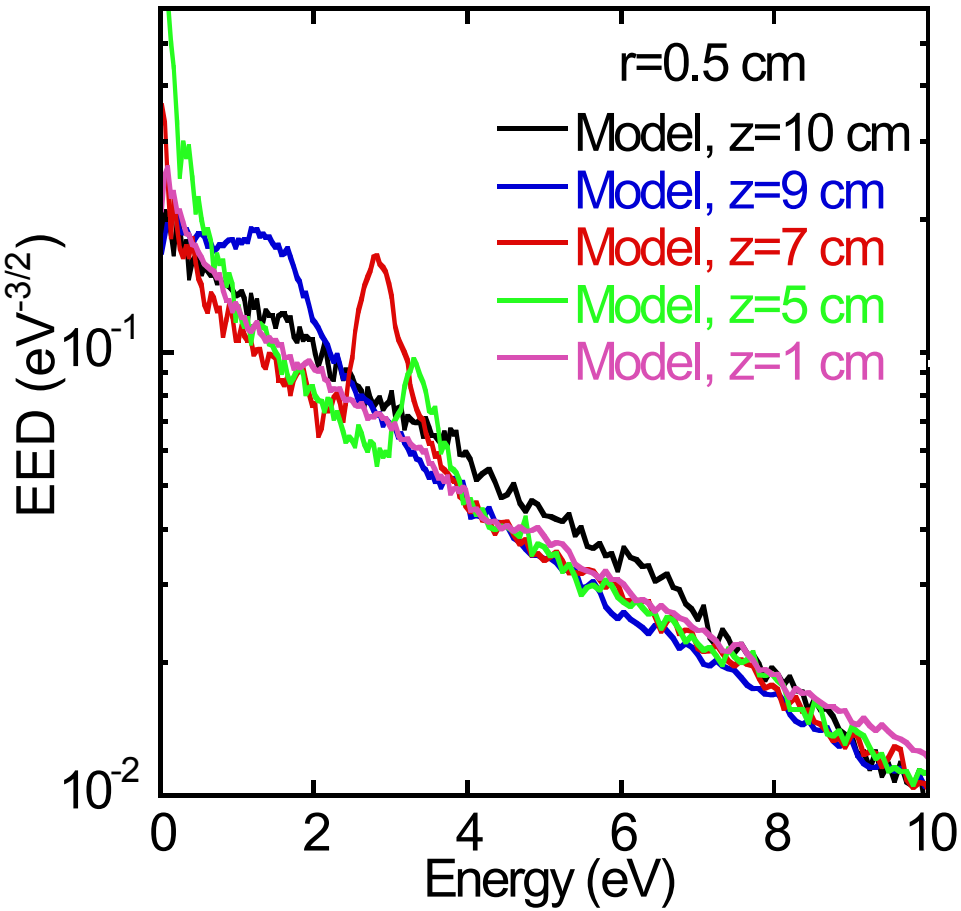


- CF_4, 10 mTorr, 150 W, 13.56 MHz, r=0, z=7.6 cm
- Model yields the same slope as experiment.
- A peak in the computed EED occurs at about 3 eV.

University of Illinois
Optical and Discharge Physics

COMPUTED EDDs IN CF_4 AT DIFFERENT HEIGHTS

- CF_4, 10 mTorr, 150 W, 13.56 MHz

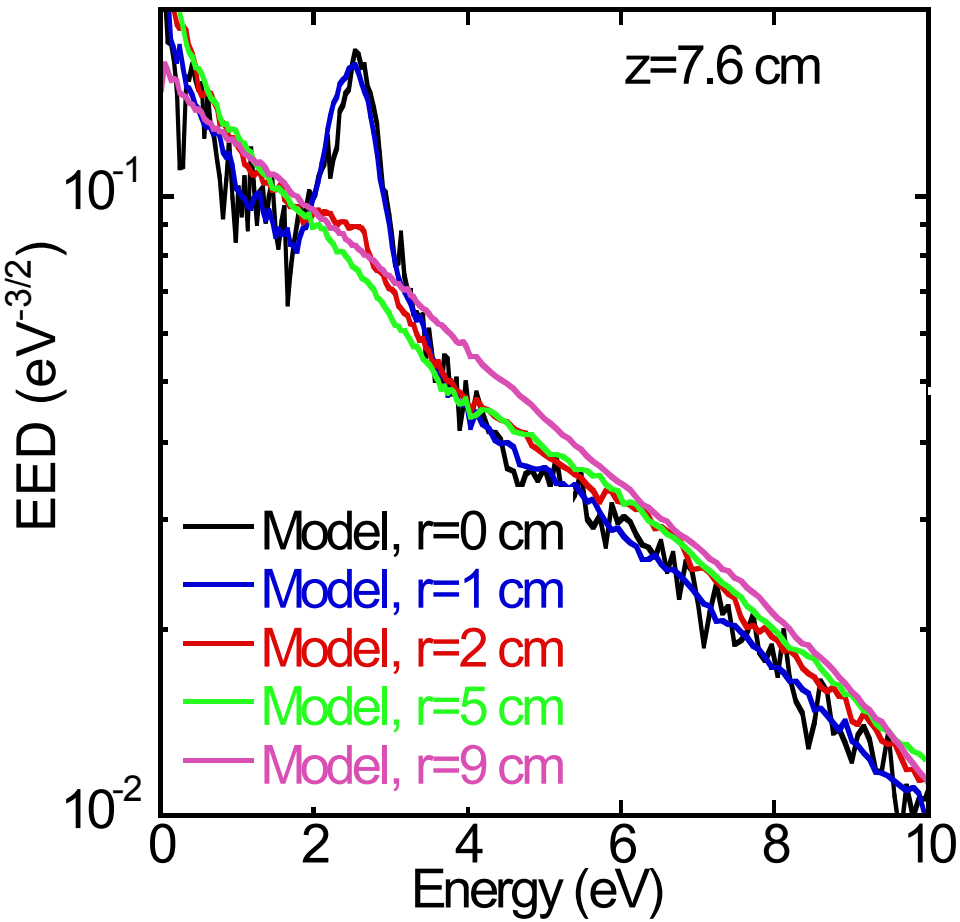


- EED is well represented by a Maxwellian distribution in the sheath
- In the bulk plasma the position of the peak shifts to higher energies approaching the skin layer.
- EED in the skin layer shows usual bi-Maxwellian features.

University of Illinois
Optical and Discharge Physics

EDDs IN CF_4 AT DIFFERENT RADII

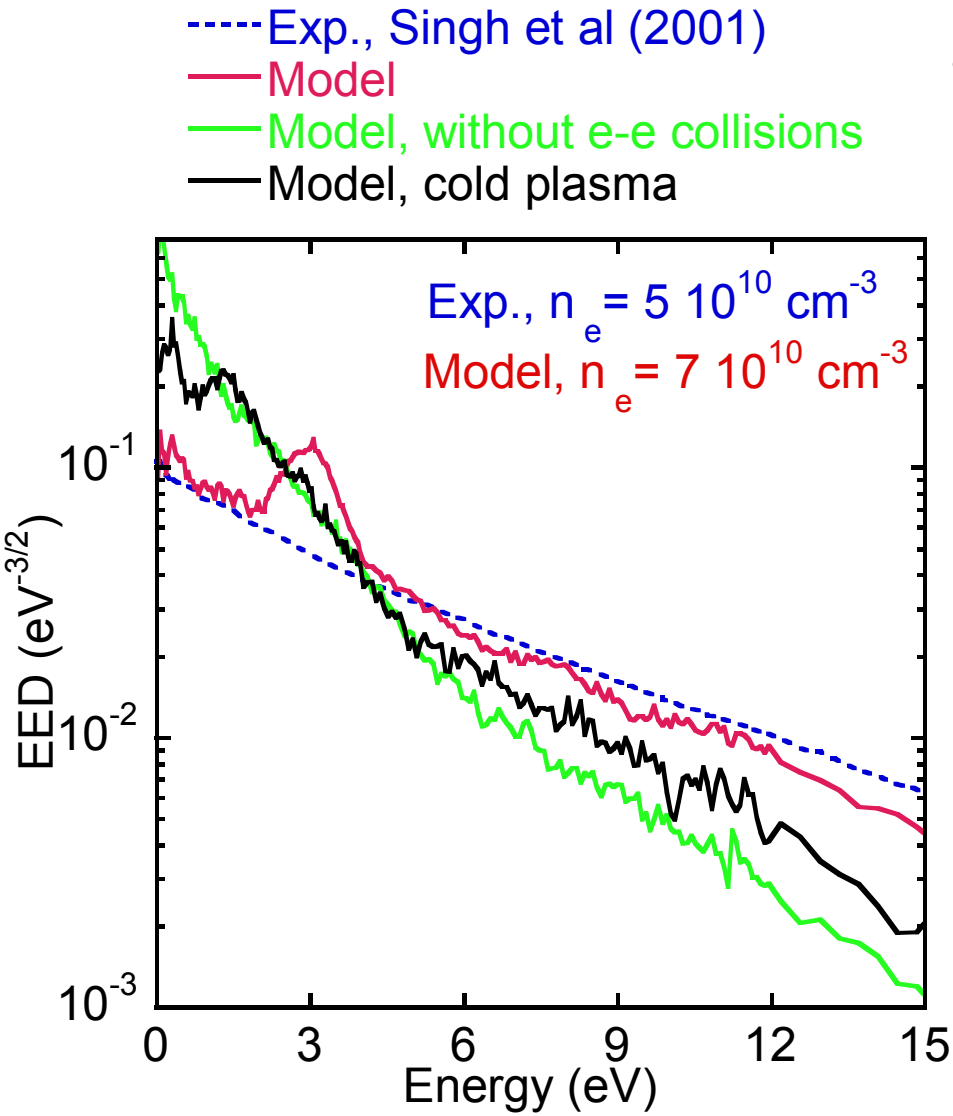
- CF_4 , 10 mTorr, 150 W, 13.56 MHz



- A peak occurs in the EEDs for radii < 2 cm.
- This peak is formed due to the flux of electrons which collisionlessly propagates from the coils to the opposite wall.
- This flux is formed as a result of interaction between the skin layer and the region of largest electron density.

University of Illinois
Optical and Discharge Physics

EXPERIMENTAL AND COMPUTED EEDs



- CF_4, 3 mTorr, 150 W, 13.56 MHz

- The energy exchange between electrons is eliminated by excluding e-e collisions.
- RF fields do not propagate beyond the normal skin layer when the cold plasma approximation is used.
- In both these cases the thermal electron motion is significantly affected.

University of Illinois
Optical and Discharge Physics

SUMMARY

- We present a new method for modeling e-e collisions in which Coulomb collisions are treated using a test particle approach and, so can be readily included in Monte Carlo simulations of low-pressure and high-density plasma systems.

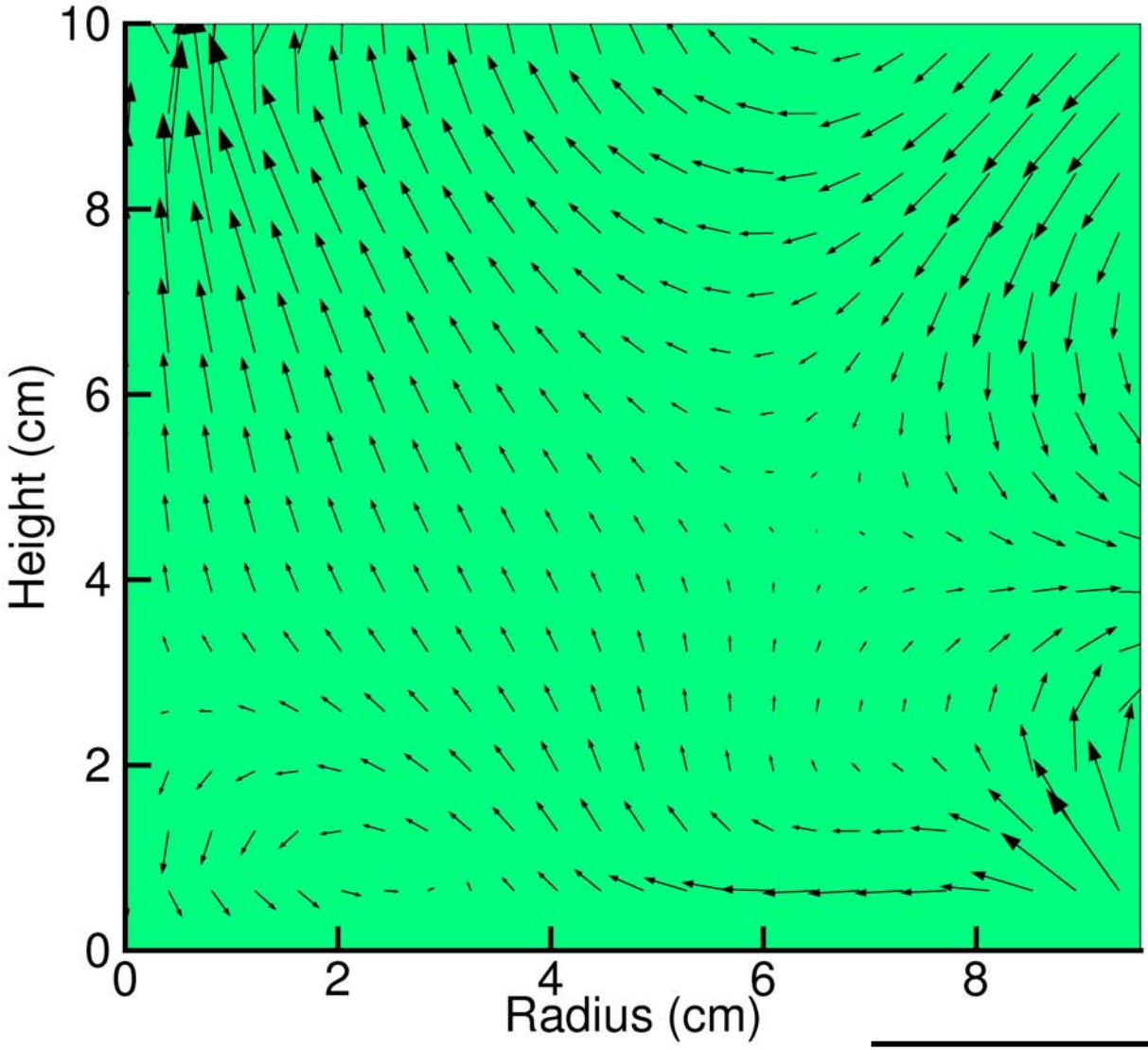
- The method was validated by comparing calculated and measured electron densities, temperatures, and electron distributions in inductively coupled argon plasma.

- The EEDs are significantly depleted at low energies in regimes dominated by non-collisional heating.

- A maximum in the computed EEDs in CF_4 depends on the thermal motion of electrons.

University of Illinois
Optical and Discharge Physics

NET CURRENT FOR CF_4, 10 mTorr, 150 W, 13.56 MHz



University of Illinois
Optical and Discharge Physics