EFFECT OF REACTOR GEOMETRY ON ION ENERGY DISTRIBUTIONS FOR PULSED PLASMA DOPING (P^2LAD)*

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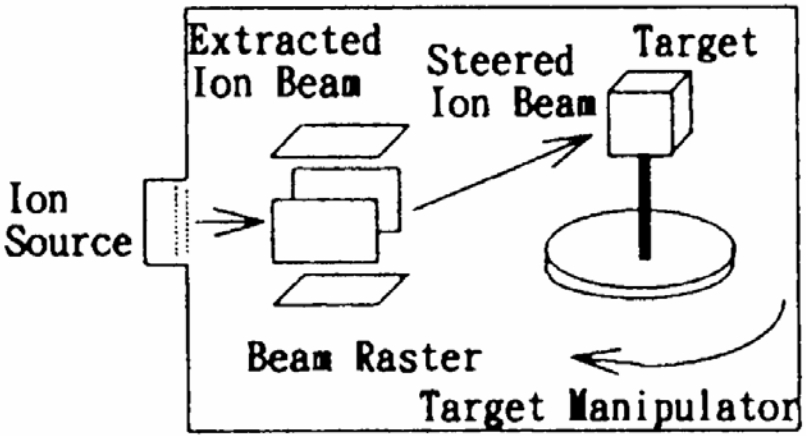
AGENDA

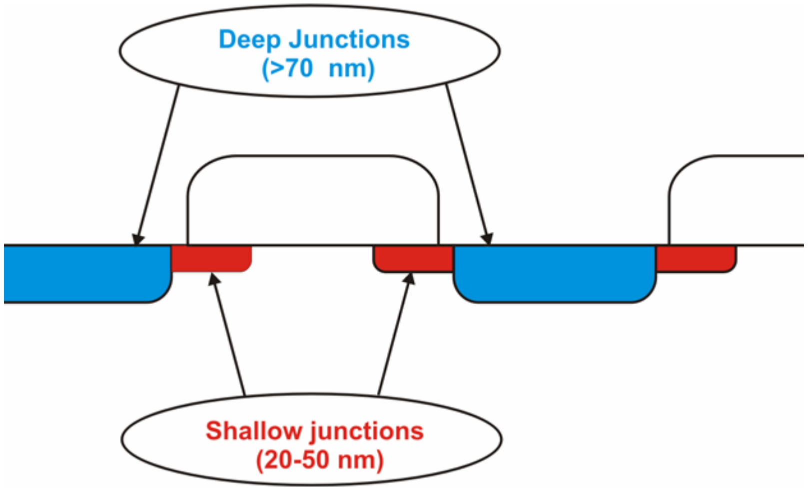
- Ion Implantation
- Pulsed Plasma Doping (P^{2}LAD)
- Approach and Methodology
- Operating Conditions
- Plasma Characteristics
- Ion Energy Distribution Functions
  - Substrate Bias Voltage
  - Power
  - Reactor Design
- Summary

ION IMPLANTATION

- **Doping by ion implantation changes band structure (n-type or p-type and controls conductivity)**
- **Beam-line ion implantation (100s keV) techniques are typically used for depths > 100s nm.**
- **Shrinking critical dimensions are increasing demands for ultra-shallow junctions (< 10s nm)**
- **Ideally for ultra-shallow junctions (20-50 nm), dopant ions should have energies < 500 eV.**



Ref: P.K. Chu et al., Mat Sci Eng R, R17, 207 (1996)

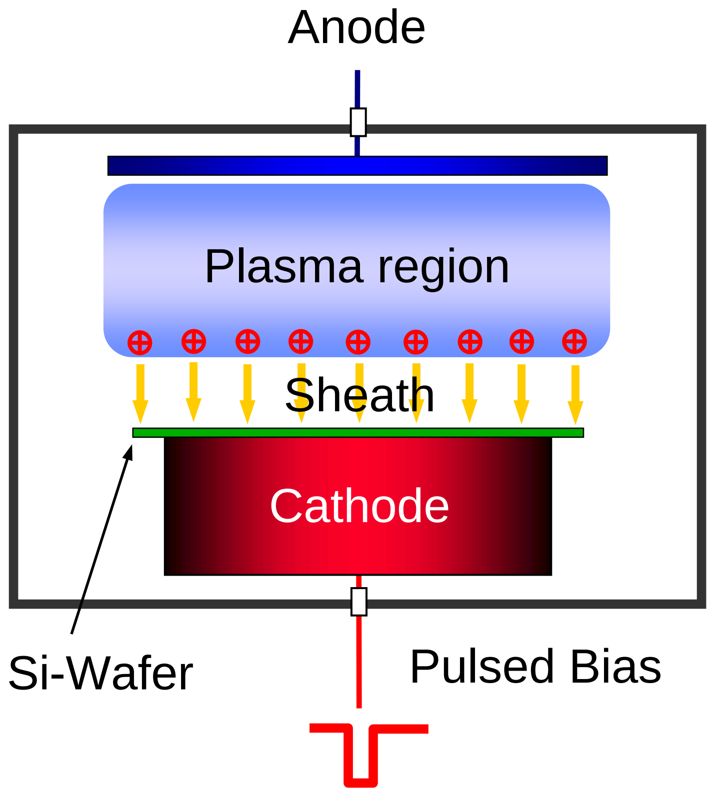


ION IMPLANTATION

- Extending beam-line ion implantation to ultra-low energies is difficult:
  - Line-of-sight process
  - Space charge induced divergence limits currents
  - Low throughputs
- Although techniques exist to overcome space charge limitations they have drawbacks:
  - Auto-neutralization produces loss of beam current.
  - Deceleration: bimodal energy distribution on the wafer
  - Molecular ion implantation: reproducibility issues.
- Plasma ion implantation is an alternative approach.
  - Pulsed plasma source containing dopant ions
  - Ions accelerated across the sheath and implanted in the wafer
  - Pulses repeated until desired dose is achieved.

P^{2}LAD (PULSED PLASMA DOPING)

- **P^{2}LAD is a pulsed plasma technique for low energy ion implantation. A plasma is produced on every pulse (many kHz).**
- **The substrate is pulsed negative to the desired implant voltage.**
- **Ions are extracted from the plasma, accelerated across the sheath and implanted into the wafer.**
- **Etching, contamination and wafer charge damage are all improved with reduced plasma-on time.**
- **High throughput at low energies.**
- **Small footprint of tool.**



Ref: VSEA ICOPS 2002

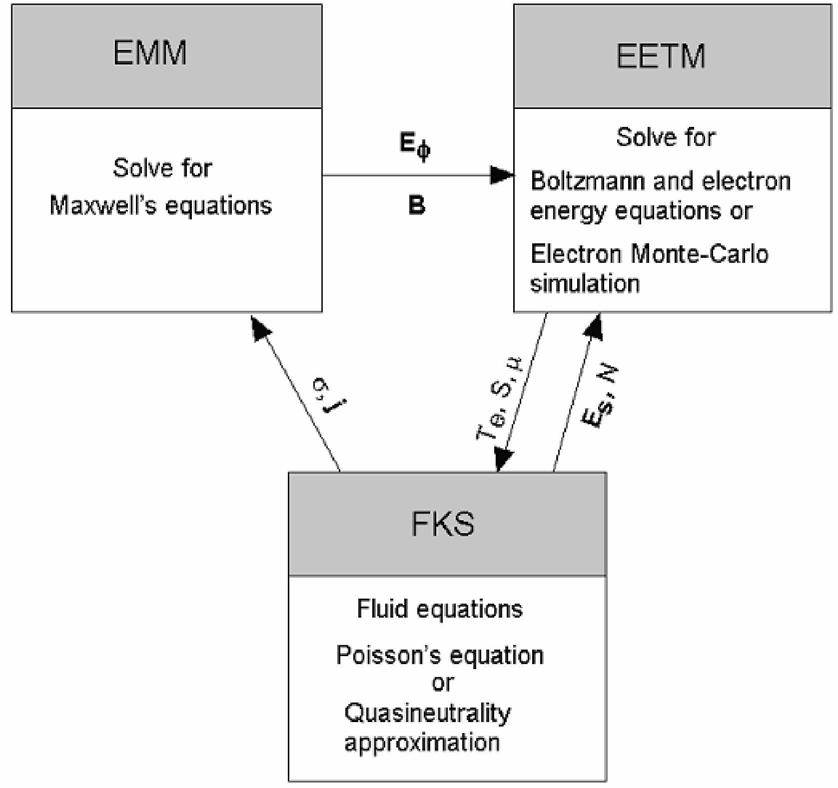
P^2LAD CHALLENGES

- Junction depth is determined by bias voltage and identity of ion species produced in the plasma:
  - Depends on geometry of source and operating conditions (pressure, gas mixture, flow rate, sheath thickness)
- Run-to-run doping repeatability related to controlling plasma parameters:
  - Plasma uniformity over wide range of implant energies
  - Materials have different secondary electron coefficients

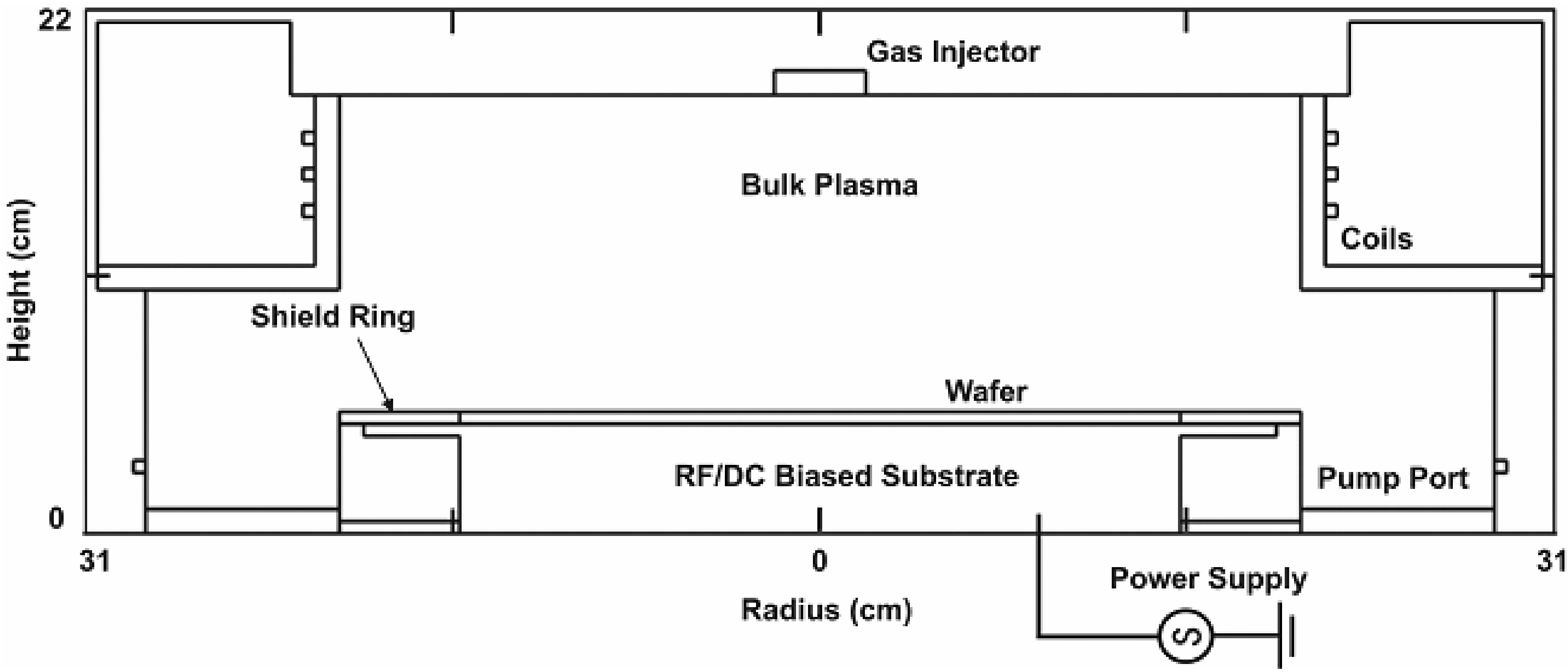
- Process Challenges:
  - Finite pulse rise/fall times produce non-monoenergetic ions.
  - Short pulse-on (μs) followed by long after-glow period (ms) may produce unwanted etching.

HYBRID PLASMA EQUIPMENT MODEL (HPEM)

- **A modular simulator addressing low temperature, low pressure plasmas.**
- **Electromagnetics Module:**
  - **Electromagnetic Fields**
  - **Magneto-static Fields**
- **Electron Energy Transport Module:**
  - **Electron Temperature**
  - **Electron Impact Sources**
  - **Transport Coefficients**
- **Fluid Kinetics Module:**
  - **Densities**
  - **Momenta**
  - **Temperature of species**
  - **Electrostatic Potentials**



P^2LAD: REACTOR GEOMETRY

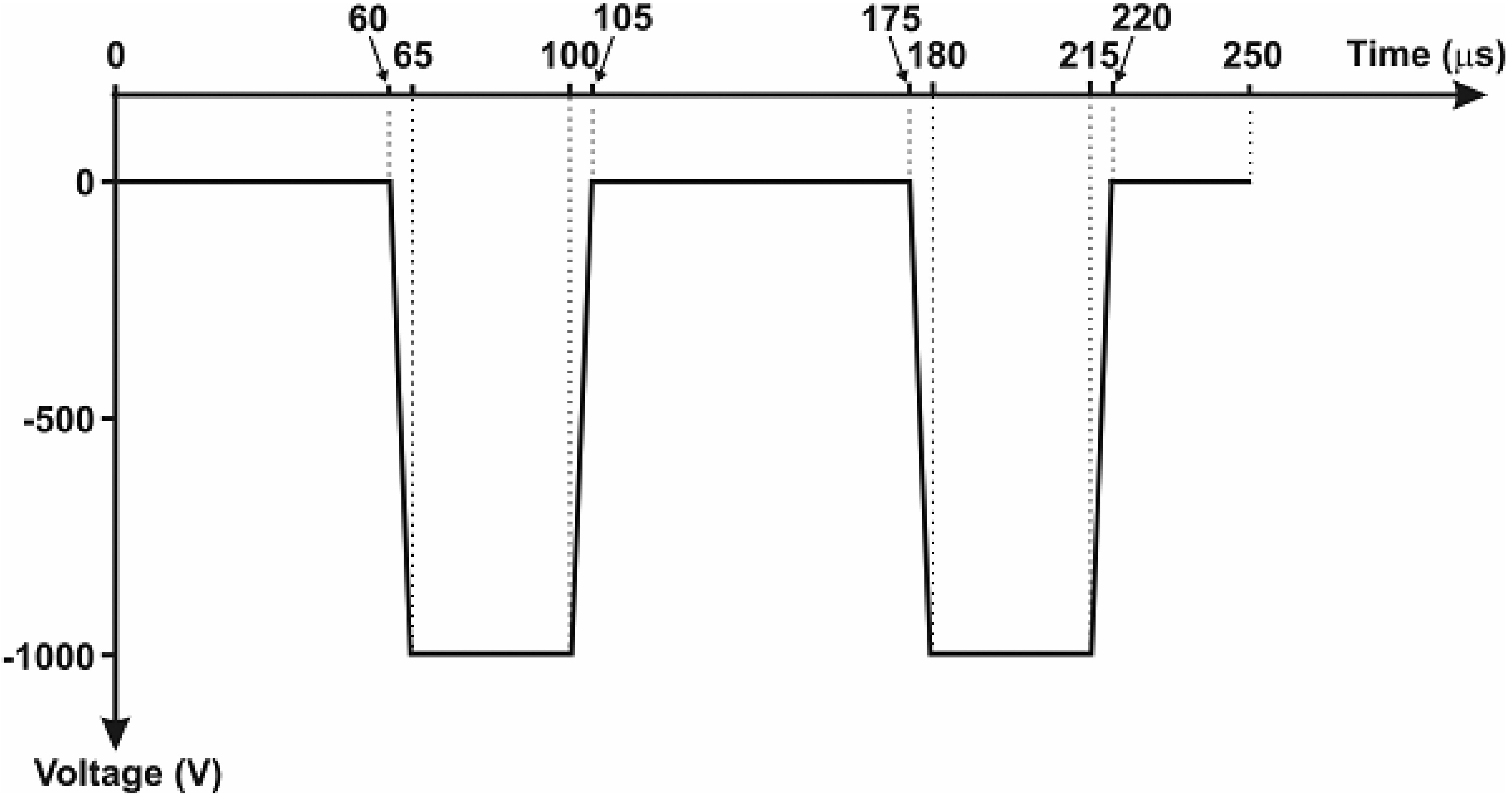


- Inductively Coupled Plasmas (ICPs) with pulsed DC biasing.
- < 10s mTorr, 10s kHz, 100s W – kW

P^2LAD: OPERATING CONDITIONS

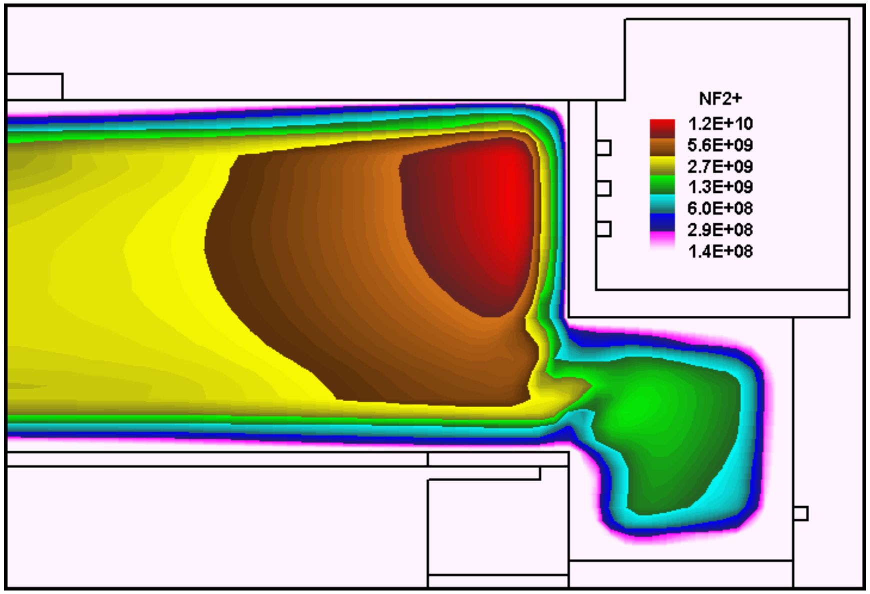
Quantity	Base Case Value
Pressure (mTorr)	**10**
Power (W)	**500**
Gas	**NF_3 (surrogate for BF_3)**
Flow-rate (sccm)	**100**
DC Bias (kV)	**1**
Pulse	**35 μs pulse width** **5 μs pulse rise** **5 μs pulse fall**
Frequency (kHz)	**~8**

P^2LAD: DC VOLTAGE PULSE

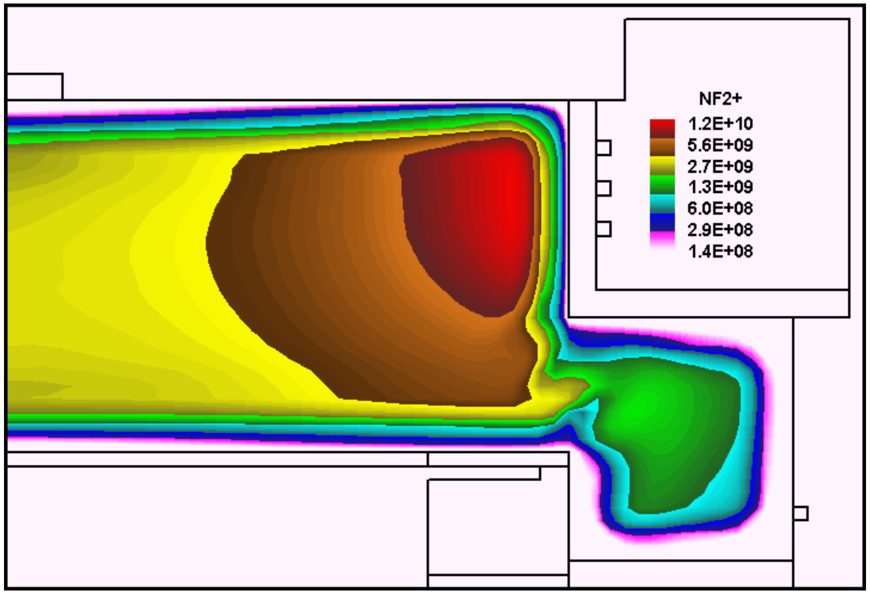


- **Finite rise and fall times (may depend on voltage) produce structure in ion energy distributions to substrate and may cause plasma instabilities.**

Ar/NF$_3$: NF$_2^+$ DENSITY



- 1,000 V; Max: 1.4 x 10^{10} cm^{-3}

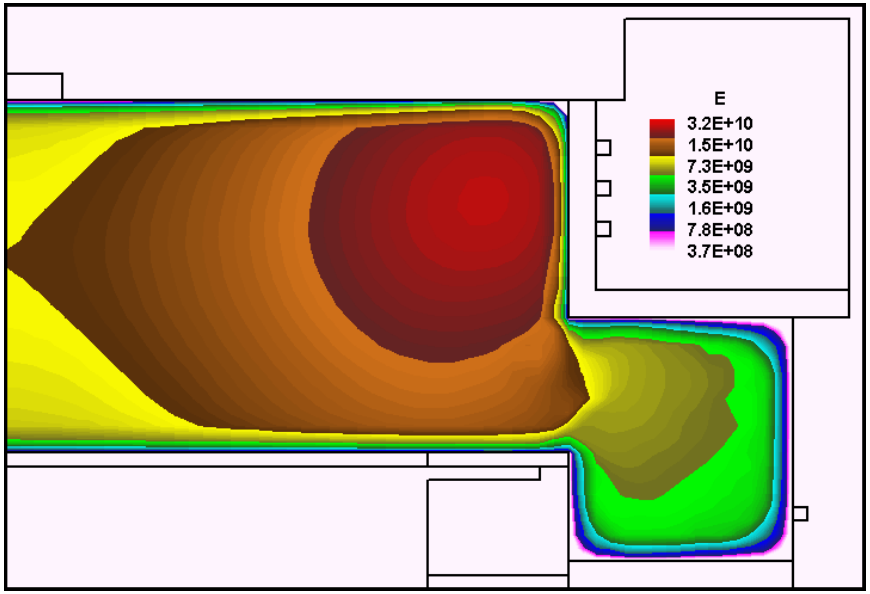


- 10,000 V; Max: 1.4 x 10^{10} cm^{-3}

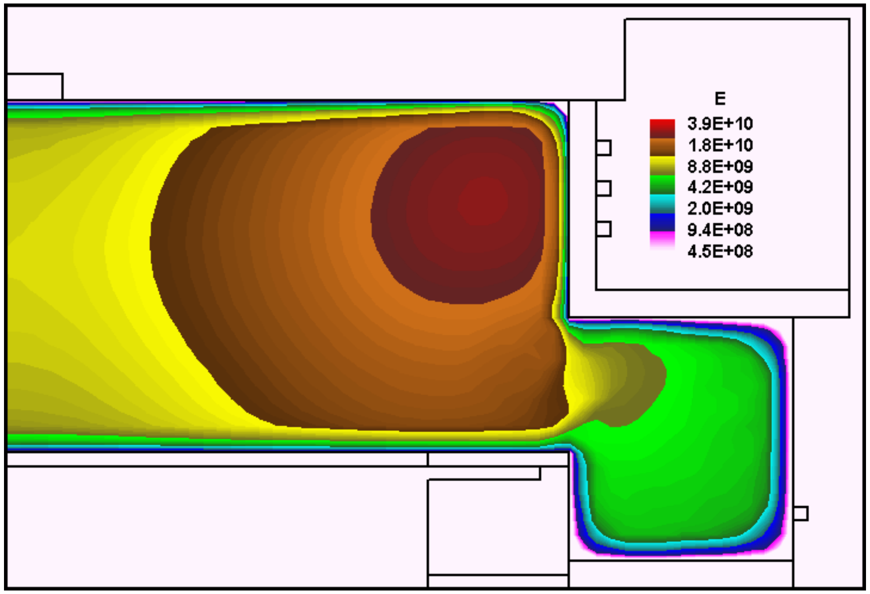
- Plasma density peaks near the coils – sheath thinner on the outside of the substrate. Note pulsation due to negative ion-positive ion transport.
- 10 mTorr, 500 W, pulsed DC, 100 sccm, Ar/NF$_3$ = 0.8/0.2

ANIMATION SLIDE

Ar/NF$_3$: ELECTRON DENSITY



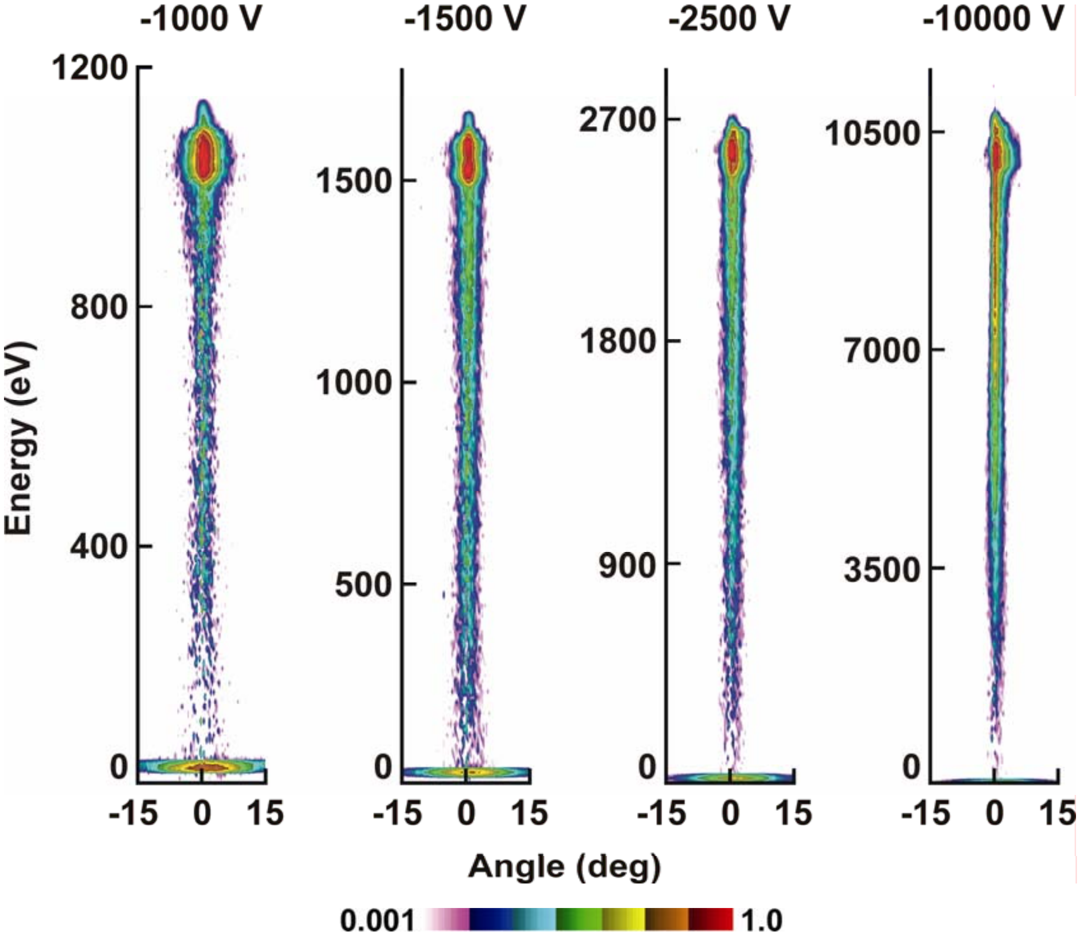
- 2,500 V; Max: 3.7 x 10^{10} cm^{-3}



- 10,000 V; Max: 4.5 x 10^{10} cm^{-3}
- Electrons rapidly move out of sheath. Ions slowly accelerated in opposite direction. Impulsive charge separation launches electro-static waves.
- Slow “infilling” of sheath at higher bias with thicker sheath.
- 10 mTorr, 500 W, pulsed DC, 100 sccm, Ar/NF$_3$ = 0.8/0.2

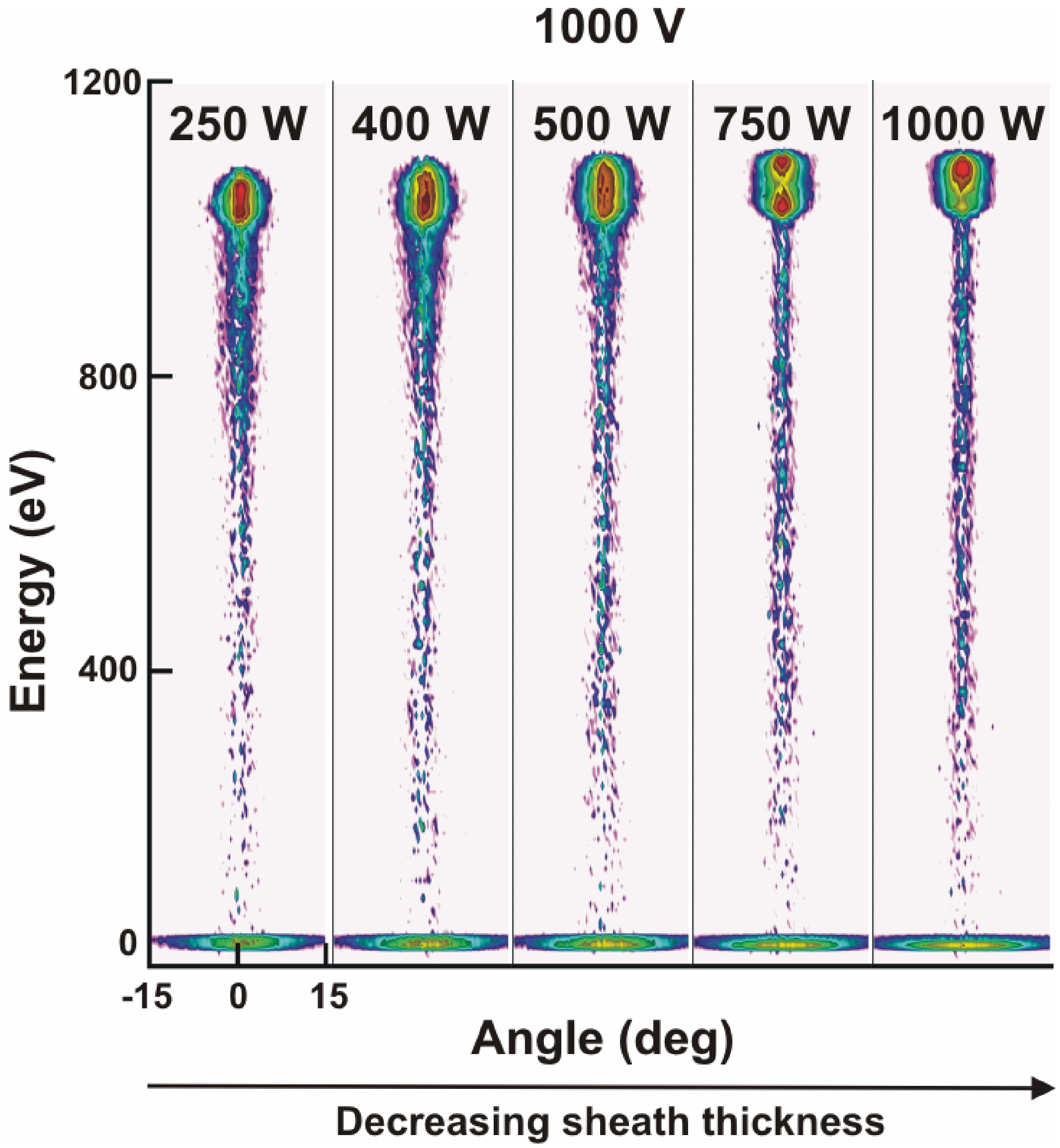
ANIMATION SLIDE

ION ENERGY ANGULAR DISTRIBUTION: PULSED DC BIAS



- IEAD peaks near applied dc bias voltage.
- Angular distribution narrows with bias on; broad without bias.
- Longer “tail” with bias due to sheath thickening (ion transit time increases and becomes collisional).
- Asymmetry results from sheath structure.

ION ENERGY ANGULAR DISTRIBUTION: ICP POWER



- **Sheath becomes thinner with increasing ICP power and plasma density.**
- **Peak energy increases increasing ICP power due to smaller transit time.**
- **"Tail" is less prominent with increasing power as is less collisional and ion transit time decreases.**

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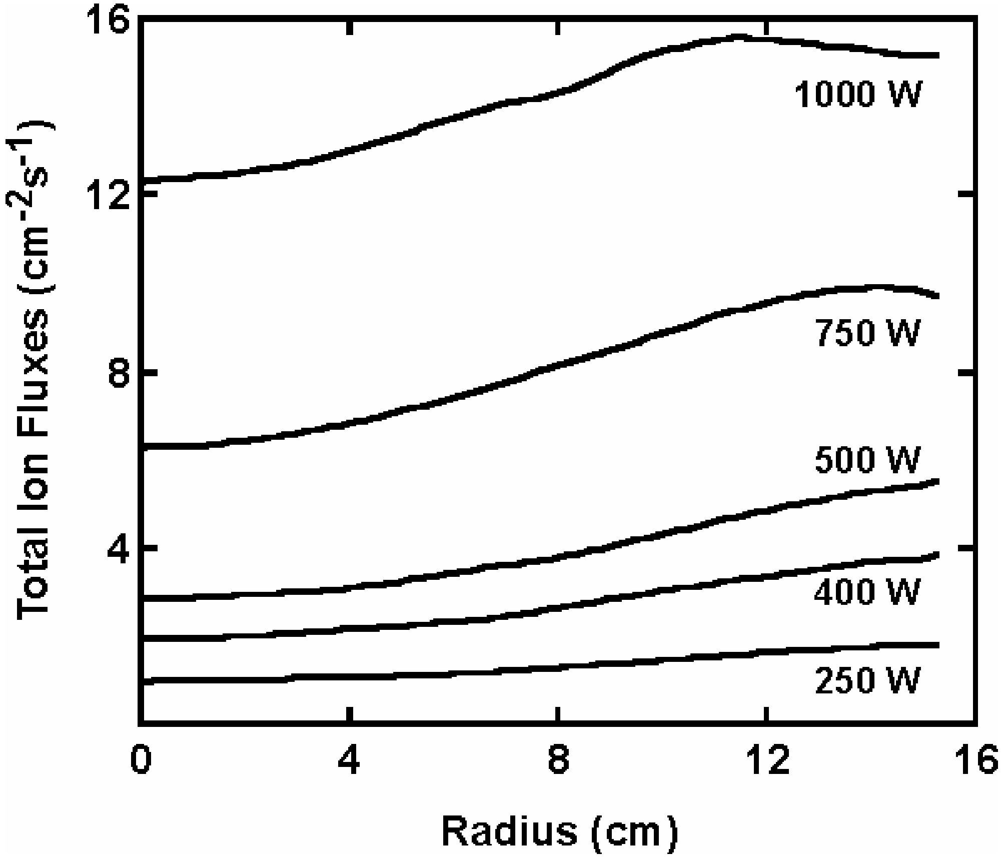
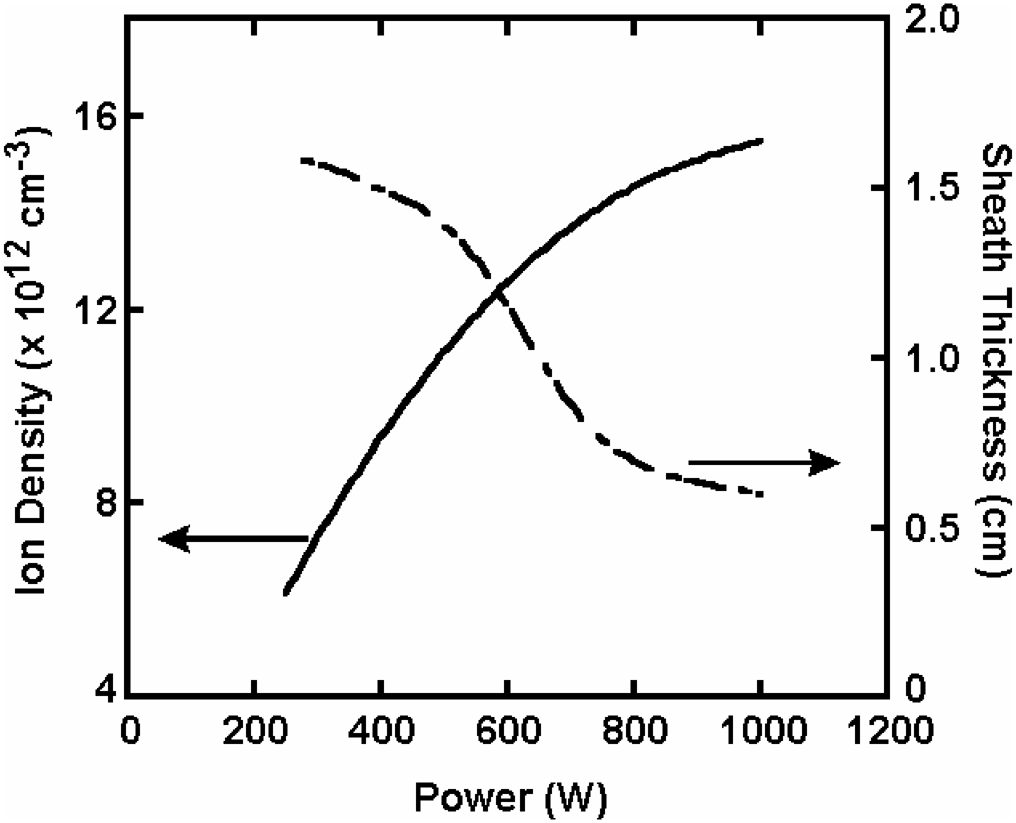
ICP POWER: TOTAL ION FLUX



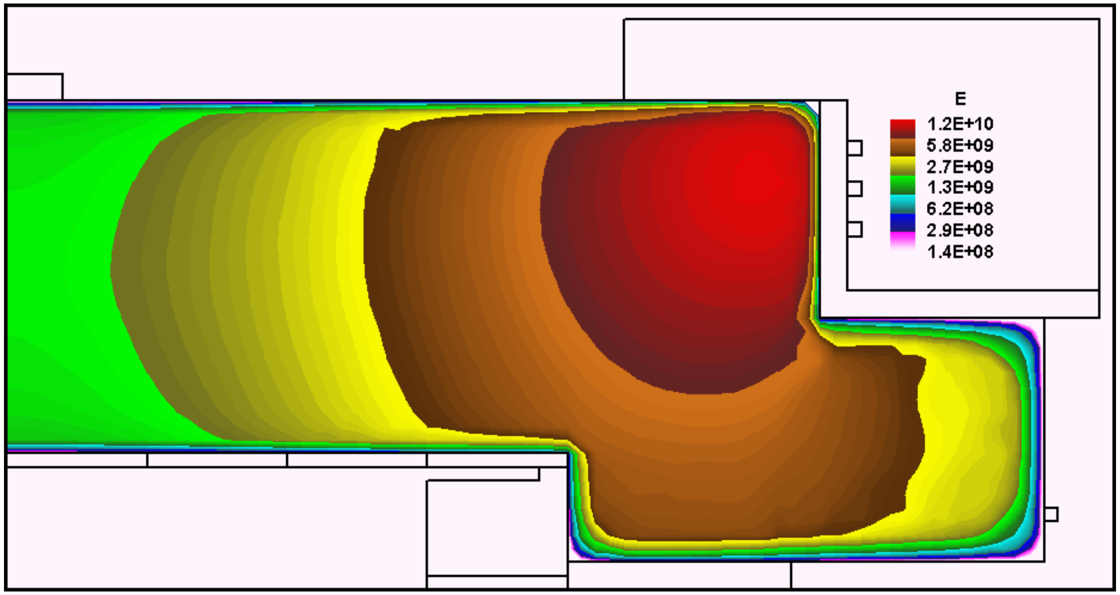
- Total ion flux increases with increasing ICP power with more light ions (more dissociation).
- Peak energy increases with increasing ICP power due to shorter transit times of lighter ions.
- 10 mTorr, -1000 V pulsed DC, Ar/NF$_3$ = 0.8/0.2, 100 sccm

ICP POWER: ION DENSITY, SHEATH THICKNESS

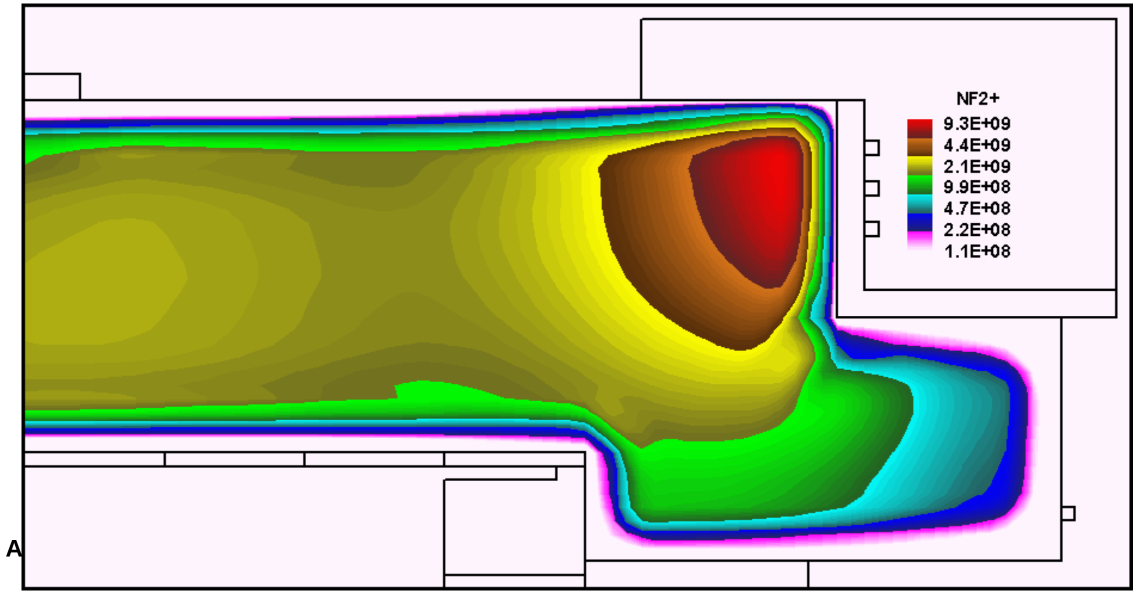


- Ion density increases with increasing ICP power.
- Sheath thickness decreases and is less collisional.
- Tail of IEAD extends to lower energies due to shorter crossing times.
- 10 mTorr, -1000 V pulsed DC, Ar/NF_3 = 0.8/0.2, 100 sccm

EXTENDED REACTOR DESIGN: [e], [NF_2^+]



- [e]; Max: 1.4×10^{10} cm^{-3}



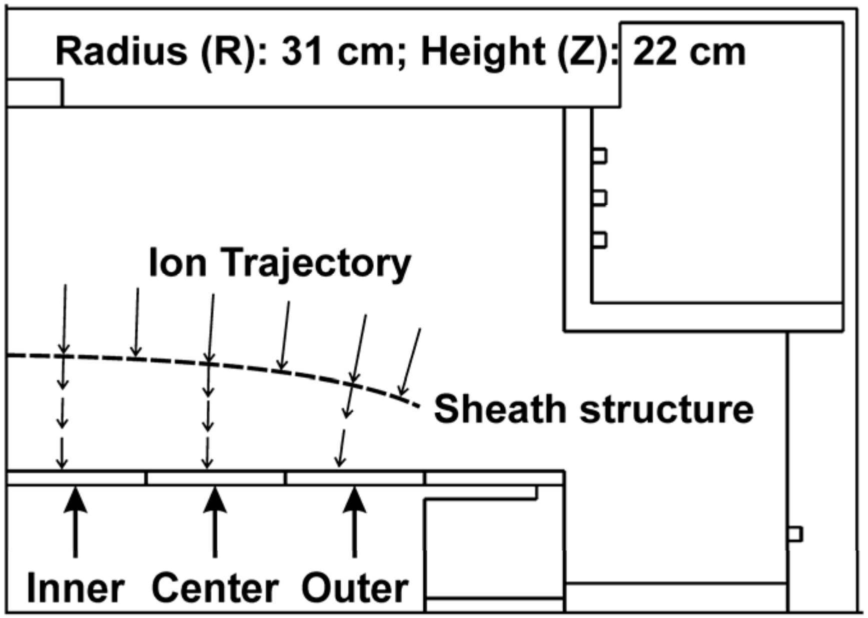
- Radius: 40 cm; Height: 22 cm
- Source of ions moved further away
- Note that the plasma density over wafer is very uniform.
- Uniform sheath structure; affects IEAD asymmetry
- 10 mTorr, 500 W, -10,000 V single pulse DC, 100 sccm, Ar/NF_3 = 0.8/0.2

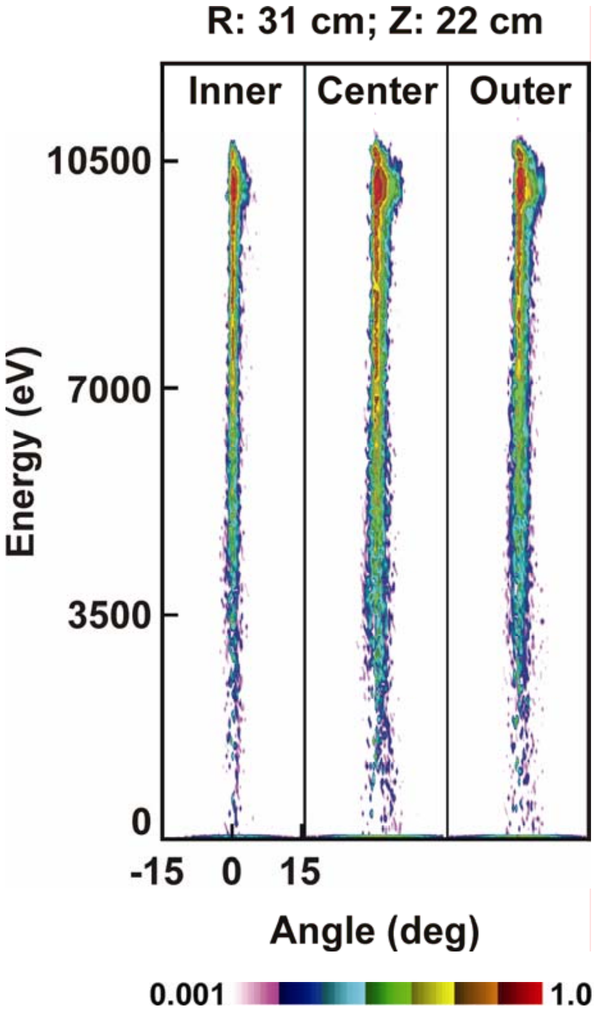
- [NF_2^+]; Max: 1.1×10^{10} cm^{-3}

ANIMATION SLIDE

Iowa State University
Optical and Discharge Physics

IEAD: STANDARD REACTOR DESIGN



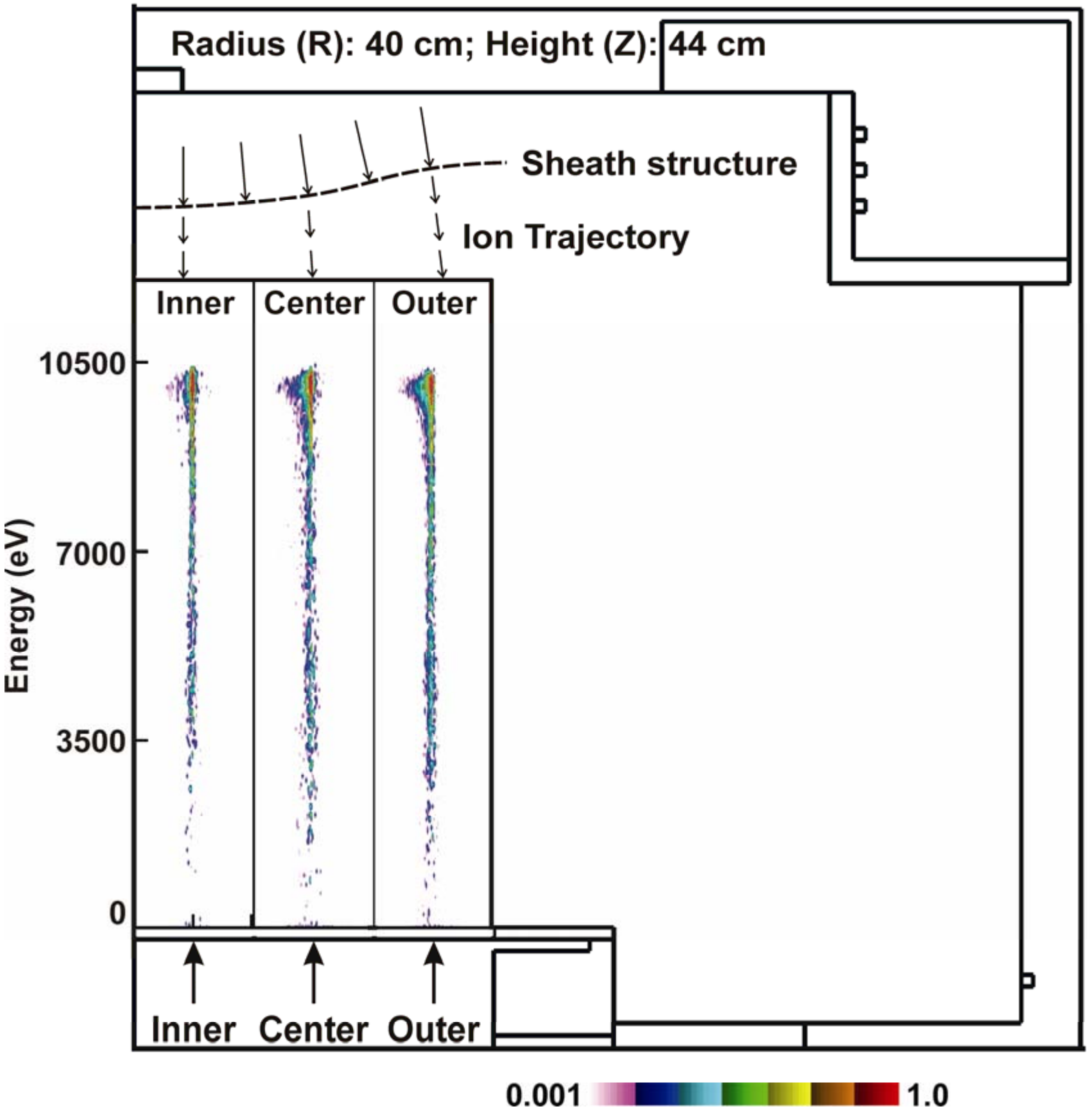


- IEAD asymmetry may result in nonuniform dopant profile.

- Control of IEAD is achieved by changing radial profile of ion flux, sheath structure.

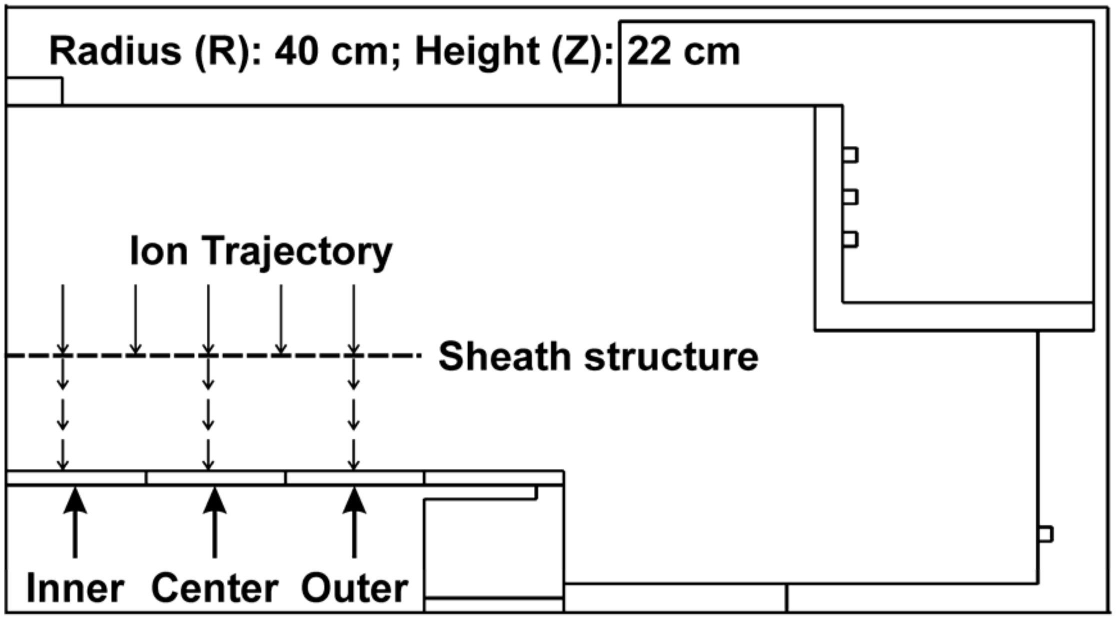
  - 10 mTorr, 500 W, -10,000 V pulsed DC, 100 sccm, Ar/NF_3=0.8/0.2

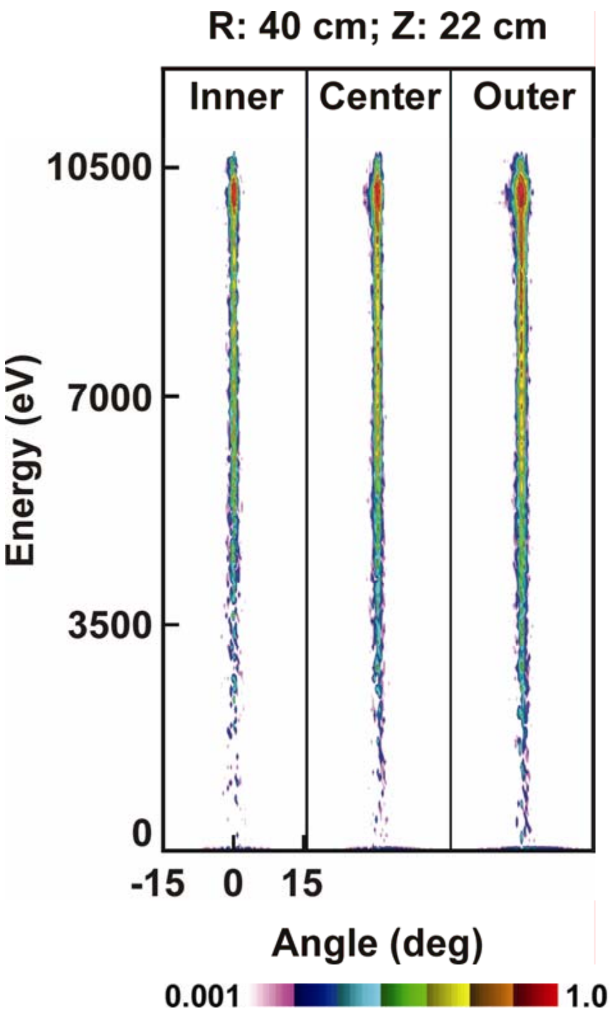
IEAD: EXTENDED REACTOR DESIGN



- **IEAD asymmetry:**
  - **Non-uniform ion density distribution**
  - **Source of ions is off-axis near the coils.**
  - **Ions preferentially approach from where ion density is maximum.**
- **Larger reactor enables ions to have diffusion dominated center peak profile.**
- **Radius: 40 cm; Height: 44 cm**

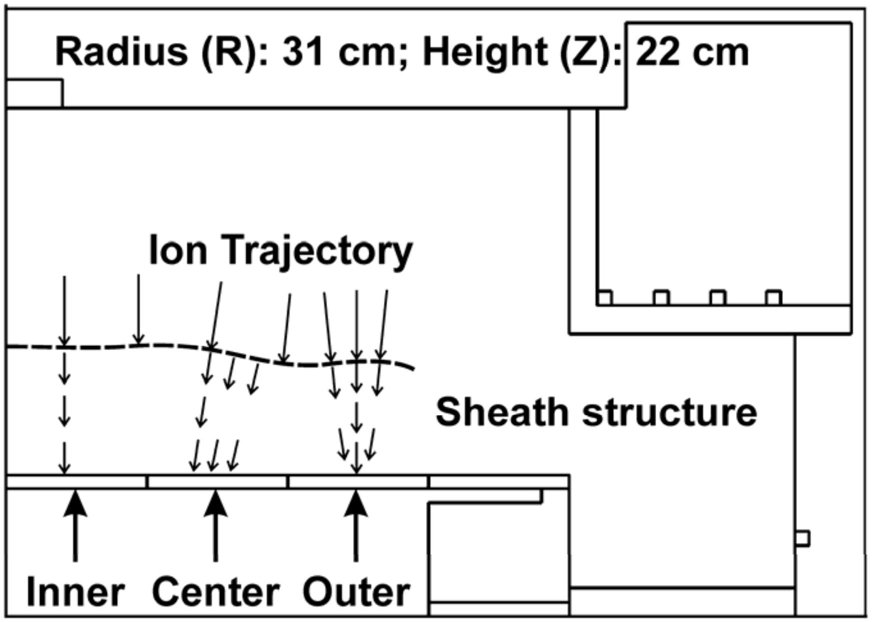
IEAD: EXTENDED REACTOR DESIGN

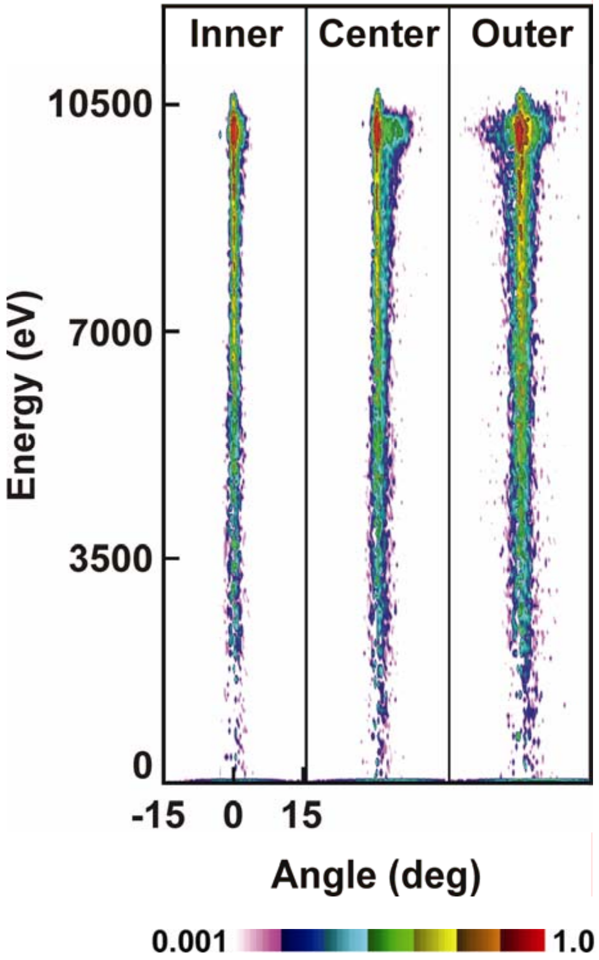




- **Radius: 40 cm; Height: 22 cm**
- **IEAD symmetry restored; angular width increases with radius.**
- **Alternately, source of ions can be controlled by changing coil positions.**

IEAD: HORIZONTAL COILS





- **IEAD asymmetry still exists; not as prominent in standard reactor.**
- **Alternately, control can be achieved by repositioning shield ring.**
- **10 mTorr, -10,000 V pulsed DC, Ar/NF$_3$ = 0.8/0.2, 100 sccm**

CONCLUDING REMARKS

- Pulsed plasma doping was investigated for low energy ion implantation to form ultra-shallow junctions.

- DC Voltage pulse characteristics important

  - If pulse is not long enough, sheath does not completely develop
  - Affects dosimetry/pulse

- Time averaged IEADs

  - Peak energy near applied dc bias voltage
  - Increasing bias narrows the angular distribution
  - Collisional sheath and finite pulse rise times: long transit time – low energy ions form “tail”
  - Peak energy increases with increasing ICP Power; less significant “tail” as a result of decreasing sheath thickness

CONCLUDING REMARKS

- **Launch of electrostatic waves can affect plasma stability.**
  - **Due to impulse of applied bias causing charge separation.**
  - **Slower application of bias must be traded off against less mono-energetic IEADs.**

- **Angular distributions are skewed at high biases due to non-uniform plasma and sheath thickness; addressable by redesign of reactor.**
  - **Uniformity achieved by changing sheath structure**
  - **Redesign includes changing coil positions, reactor dimensions or shield ring position**