Control of heating dynamics and distribution functions in technological plasmas

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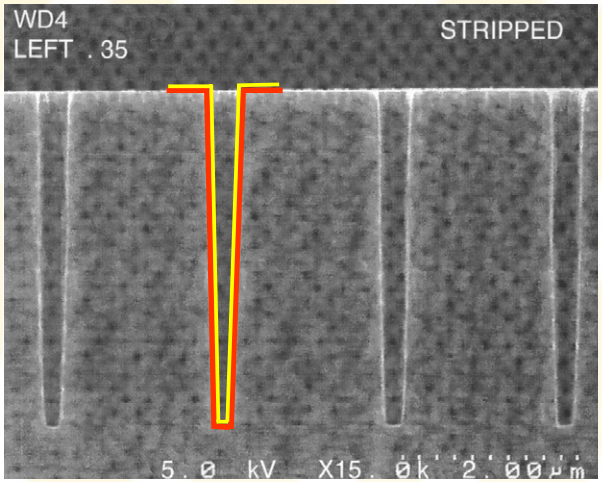
Societal relevance of low temperature plasmas

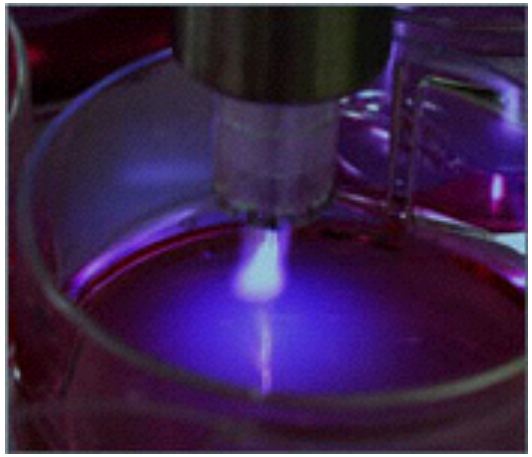


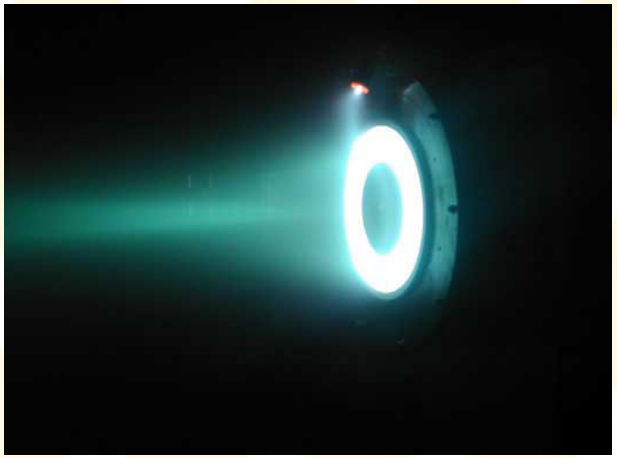
Plasma Etching, Sputtering and Deposition processes on microscopic scales are irreplaceable tools for semiconductor manufacturing and other key industries (automotive, tool manufacturing, textiles, etc.).

Without plasma technology no laptop and smartphone would exist.

In order to fulfill Moore's law in the future, intensive research in low temperature plasma science is required to overcome process limitations.

Societal relevance of low temperature plasmas



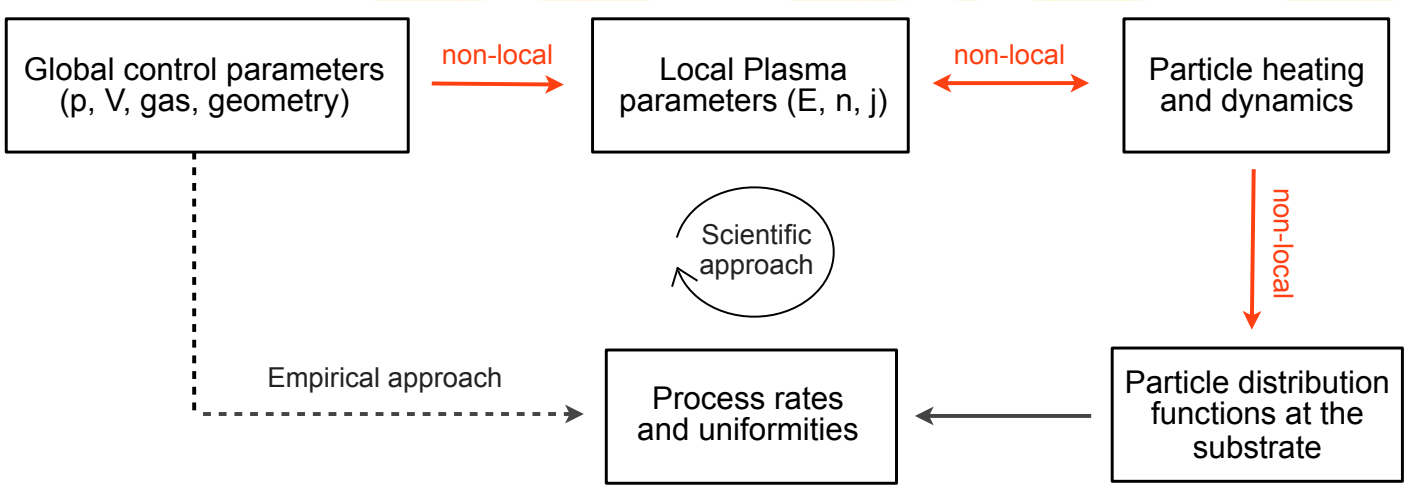


Biomedical applications, light sources, plasma and thrusters.

There is little understanding of the physics of plasma-liquid and plasma-human tissue interactions required for plasma medical applications.

Plasma surface interactions are generally poorly described by models/simulations due to unknown surface coefficients (secondary electron emission, particle reflection, etc.).

Research Frontier: It's all about control

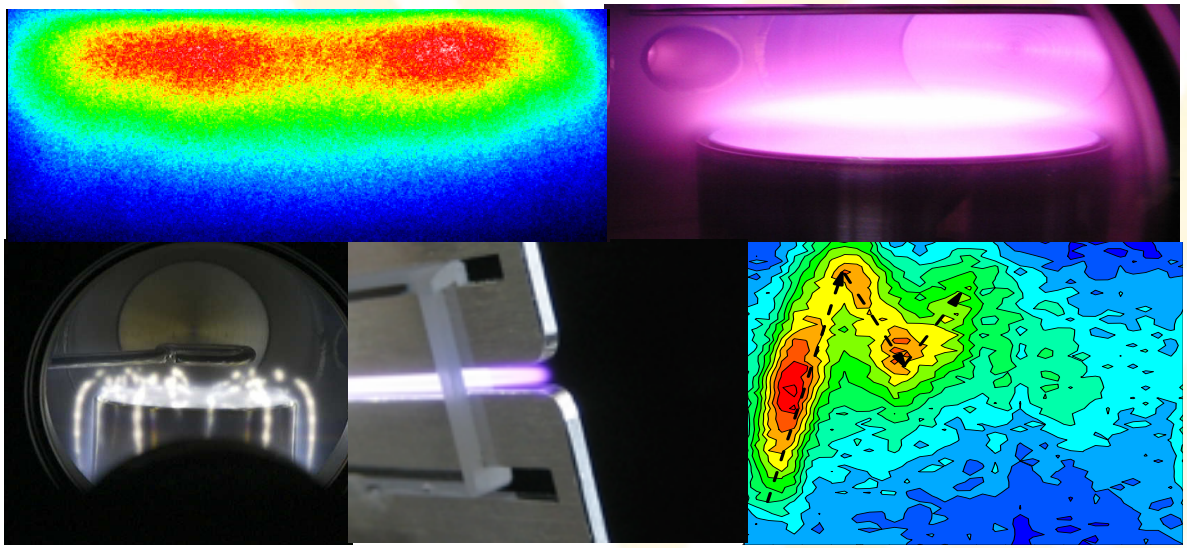


Plasma processing applications are usually optimized empirically without understanding the heating dynamics of electrons, ions, and neutrals.

Efficient process optimization must be based on a detailed scientific understanding of non-local effects of global control parameters on the heating dynamics → *predictive control of plasma kinetics*.

Based on these insights electron and ion *energy distribution functions can be tailored* and process rates as well as uniformities can be optimized.

Required approach



A combination of *state-of-the-art experimental diagnostics, numerical simulations, and analytical models* is required to get a complete understanding of particle heating dynamics and their links to the formation of flux-energy distribution functions.

Often (sub-)nanosecond time resolution is required to resolve the fastest timescales. This is an extreme (experimental) challenge.

Fundamental understanding must be transferred from academia to industry (collaborations, industrially relevant reactive gas mixtures).

Impact on Plasma Science - it's a hot topic

Plasma Sources Science and Technology

Submission date: 31 January 2015

iopscience.org/psst

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems

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Department of Energy Plasma Science Center

Call for papers

Special issue on "Electron heating in technological plasmas"

Thomas Mussenbrock (Ruhr-Universität Bochum, Germany)
Julian Schulze (West Virginia University, USA)

PHYSICS OF PLASMAS **20**, 101501 (2013)

Preface to Special Topic: Electron kinetic effects in low temperature plasmas

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[2]*RF Plasma Consulting, Brookline, Massachusetts 02446, USA and Michigan Institute for Plasma Science and Engineering, University of Michigan, Ann Arbor, Michigan 48109, USA*
[3]*CFD Research Corporation, Huntsville, Alabama 35805, USA*

Heating dynamics and concepts to tailor flux-energy distributions of different particle species are widely accepted as important research topics in low temperature plasma science.

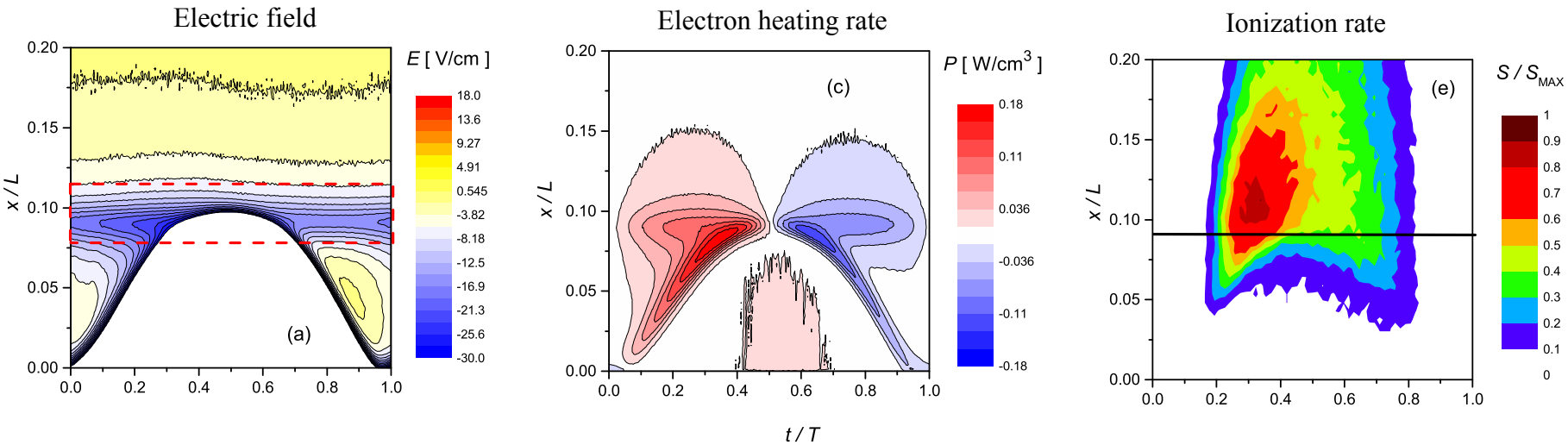
J. Phys. D: Appl. Phys. **45** (2012) 253001 (37pp)

REVIEW ARTICLE

The 2012 Plasma Roadmap

Seiji Samukawa[1], Masaru Hori[2], Shahid Rauf[3], Kunihide Tachibana[4], Peter Bruggeman[5], Gerrit Kroesen[5], J Christopher Whitehead[6], Anthony B Murphy[10], Alexander F Gutsol[8], Svetlana Starikovskaia[9], Uwe Kortshagen[7], Jean-Pierre Boeuf[11], Timothy J Sommerer[12], Mark J Kushner[13], Uwe Czarnetzki[14] and Nigel Mason[15]

Fundamental understanding of electron heating in CCPs



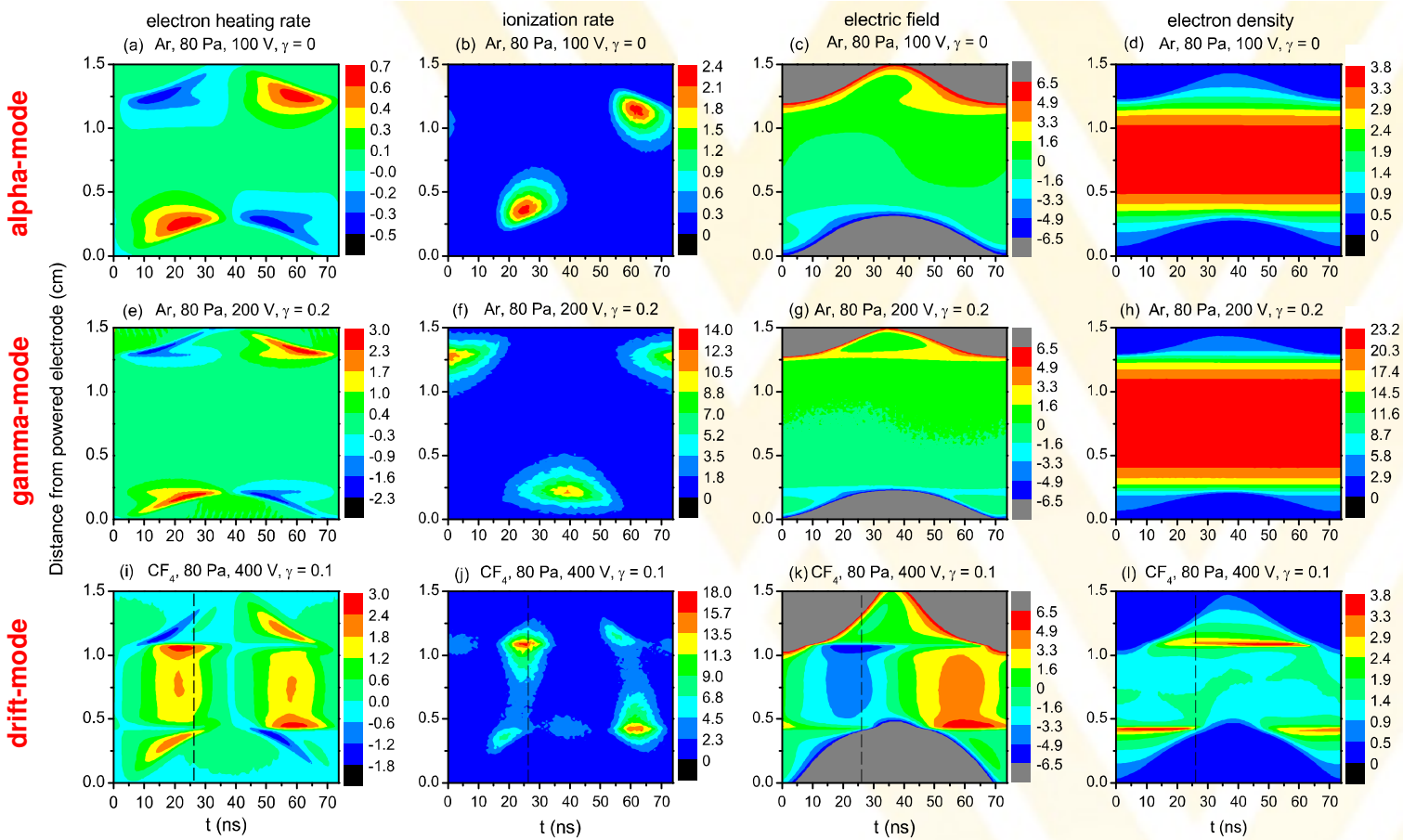
J. Schulze et al. 2015 Plasma Sourc. Sci. Technol. 24 015019

Discharge conditions (PIC/MCC simulation): Argon, 20 Pa, 5 cm electrode gap, 13.56 MHz, 400 V

Current understanding: - Electrons are heated collisionlessly by the expanding RF sheaths.
- There is no E-field outside the sheaths and symmetry in time.
- The current is sinusoidal.

Recent findings: - There is essentially no collisionless heating (Lafleur et al. 2015 PSST 24 044002).
- There are strong electric fields outside the sheaths and a temporal asymmetry.
- The current is often non-sinusoidal (resonances, Mussenbrock et al. 2008 PRL 085004)

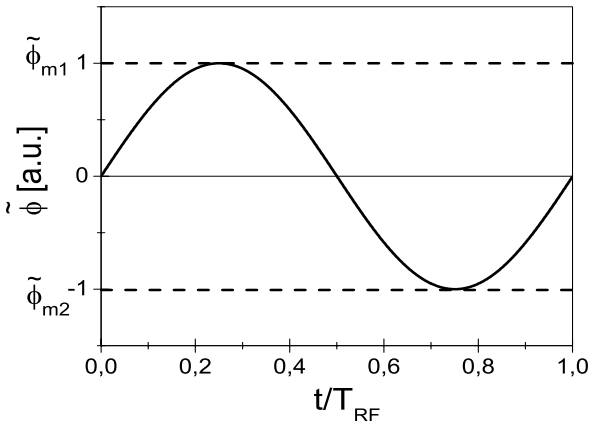
A variety of electron heating modes

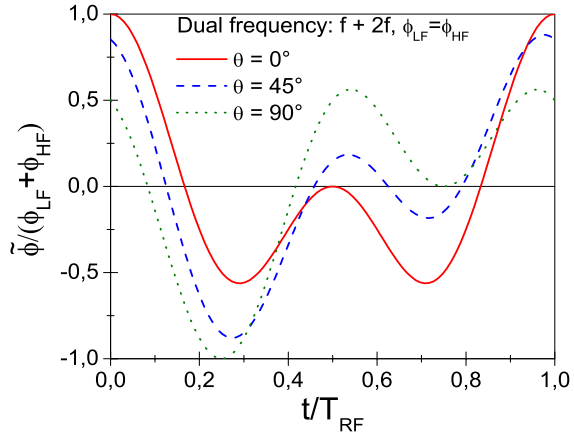


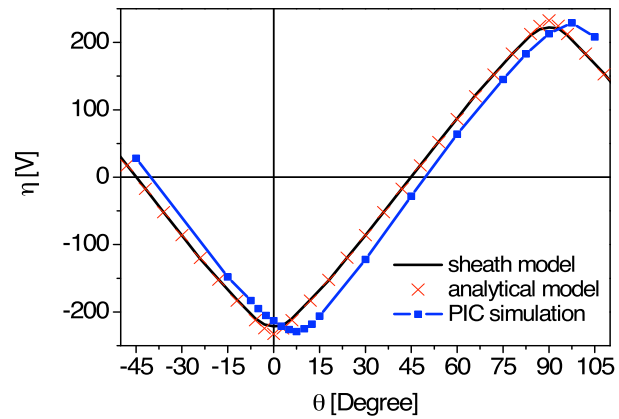
Different heating modes exist and are only partially understood. The presence of a different mode drastically changes process relevant plasma parameters. Mode transitions must be studied.

J. Schulze et al. 2011 Phys. Rev. Lett. 107 275001

The Electrical Asymmetry Effect







In RF plasmas, the DC self-bias (difference between mean sheath voltages) is an important parameter to control the ion energy at the electrodes:

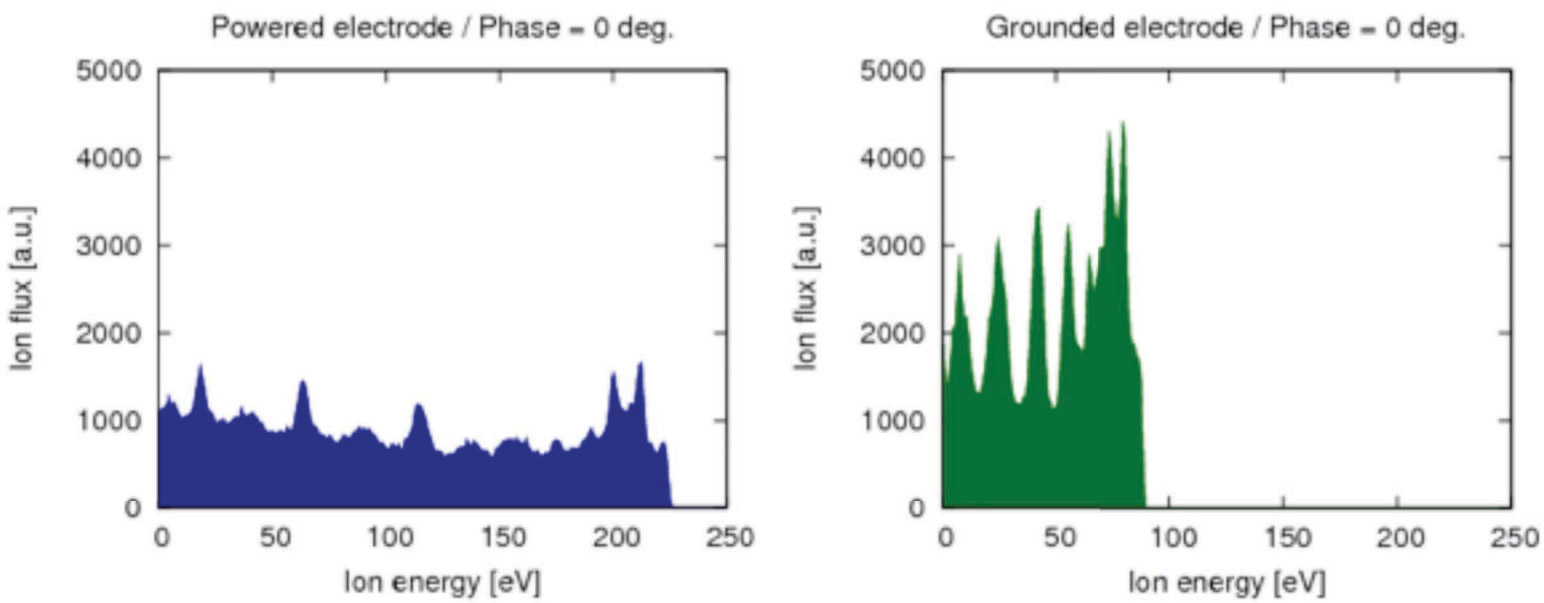
$$\eta = -\frac{\tilde{\phi}_{m1} + \varepsilon\tilde{\phi}_{m2}}{1+\varepsilon} \qquad \varepsilon = \left|\frac{\hat{\phi}_{sg}}{\hat{\phi}_{sp}}\right| \approx \left(\frac{A_p}{A_g}\right)^2 \frac{\bar{n}_{sp}}{\bar{n}_{sg}}$$

In classical CCPs, the extrema of the driving voltage waveform are identical and a DC self bias can only be generated via $\varepsilon \neq 1$, i.e. a geometric discharge asymmetry. The EAE allows to generate a DC self bias electrically by tailoring the driving voltage waveform, e.g. different extrema, different slopes (sawtooth).

B. G. Heil, J. Schulze et al. 2008 *IEEE Trans. Plasma Science* 36 1404

B. G. Heil et al. 2008 *J. Phys. D* 41 165202

Electrical control of the IEDF



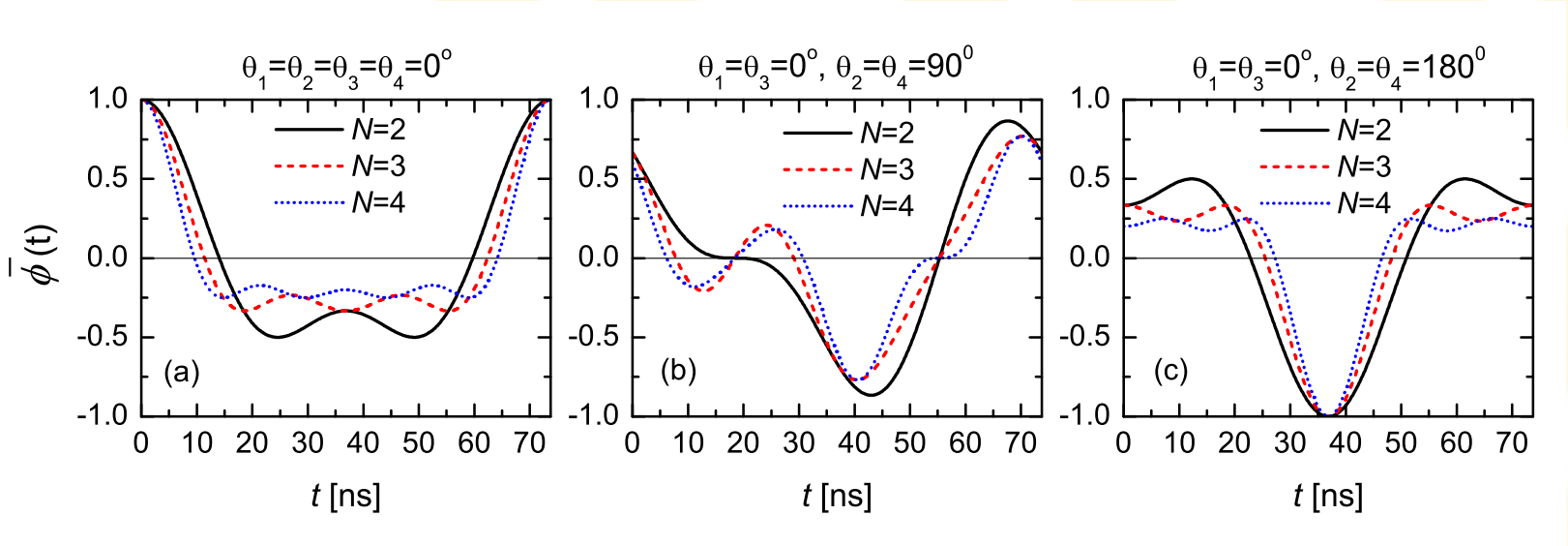
The IEDF can be controlled by tuning the phase. The role of the electrodes can be reversed electrically.

This effect is strongly affected by the electron heating mode and works differently in different chemistries, pressures, frequencies. Very little is known about this.

The EAE allowed to improve the efficiency of PECVD processes (Si:H deposition) by a factor of 3. Other applications must be studied (etching, sputtering).

Z. Donko et al. 2009 *J. Phys. D* 42 025205

Voltage waveform tailoring



In principle every driving voltage waveform can be realized as a Fourier Series of N consecutive harmonics of a fundamental frequency, f:

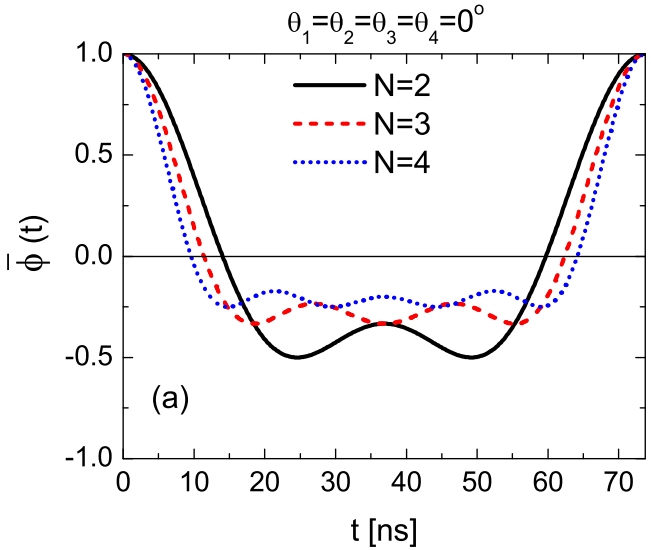
$$\phi(t) = \sum_{k=1}^{N} \phi_k \cos\left(2\pi k f t + \theta_k\right) \qquad \text{with} \qquad \phi_{tot} = \sum_{k=1}^{N} \phi_k$$

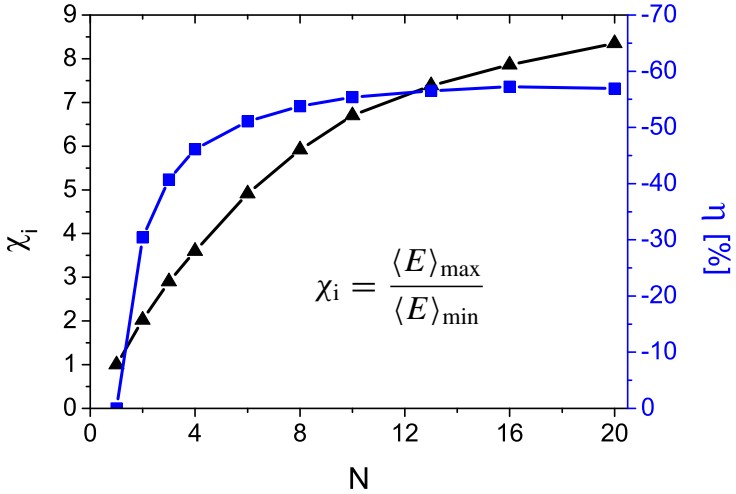
In this way the electron heating dynamics can be tailored on a ns-timescale and the sheath voltage waveform can be tailored to customize IEDFs.

J. Schulze et al. 2011 Plasma Sourc. Sci. Technol. 20 015017

A. Derzsi et al. 2013 Plasma Sourc. Sci. Technol. 22 065009

Optimization of the EAE (simulation)





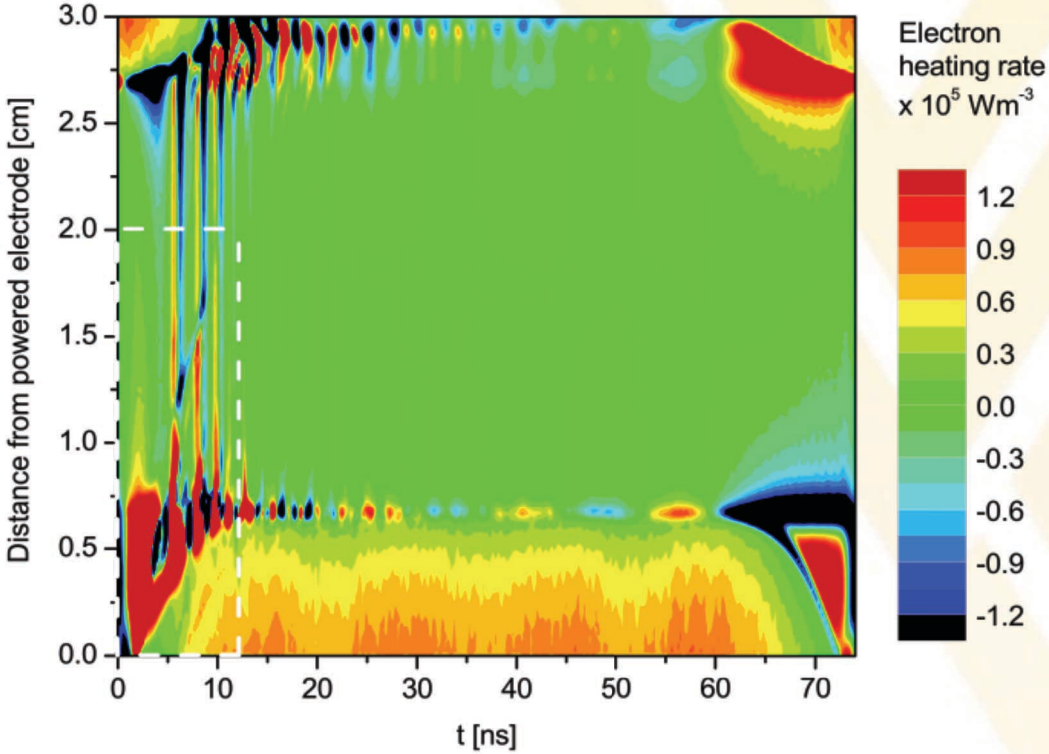
Conditions: Argon, 10 Pa, 2 cm gap, f = 13.56 MHz, ϕ_{tot} = 300 V, optimized harmonics' amplitudes.

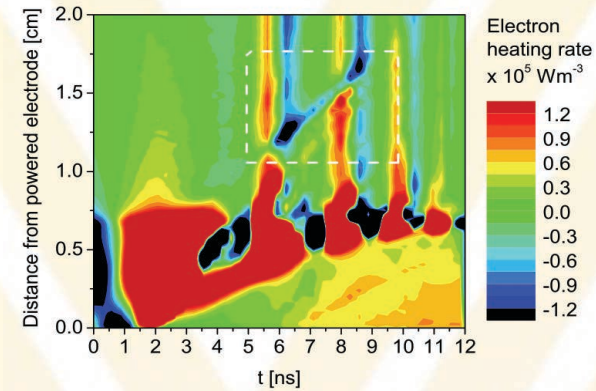
Adding more consecutive harmonics to the driving voltage waveform, while keeping the total voltage amplitude constant, allows to generate a stronger DC self bias and to control the mean ion energy over a larger range.

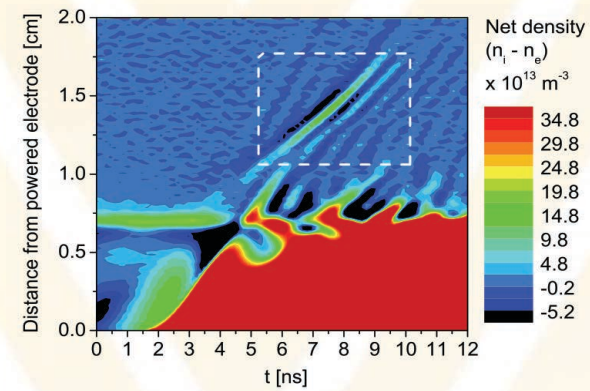
This must be studied experimentally in different plasmas sources, gas mixtures, etc.

J. Schulze et al. 2011 *J. Phys. D* 20 015017

Complex heating dynamics (3 Pa, 800 V, N = 4)





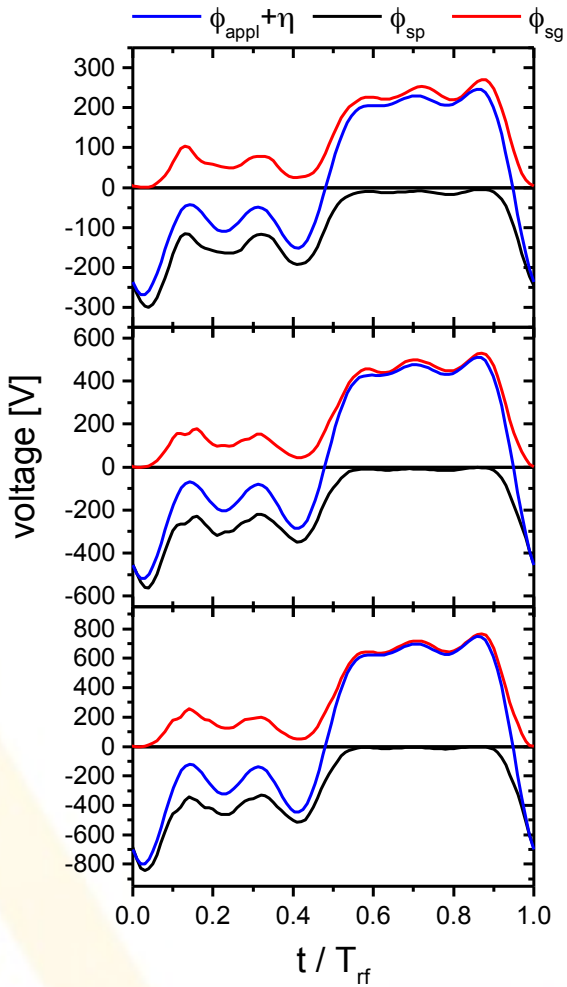


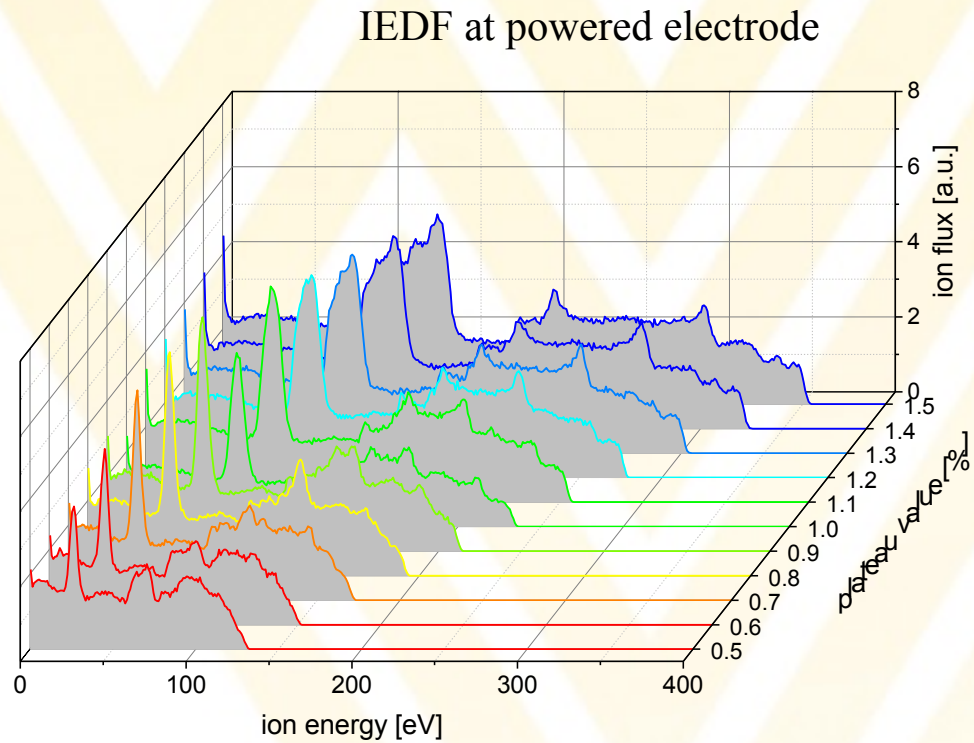
The electron heating dynamics in multi-frequency CCPs are complex and cannot be explained by classical concepts of stochastic heating.

Ambipolar electron heating, NERH, waves, and interference effects play an important role.

J. Schulze et al. 2014 IEEE Trans. on Plasma Sci. 42 2780

Customized ion energy distributions



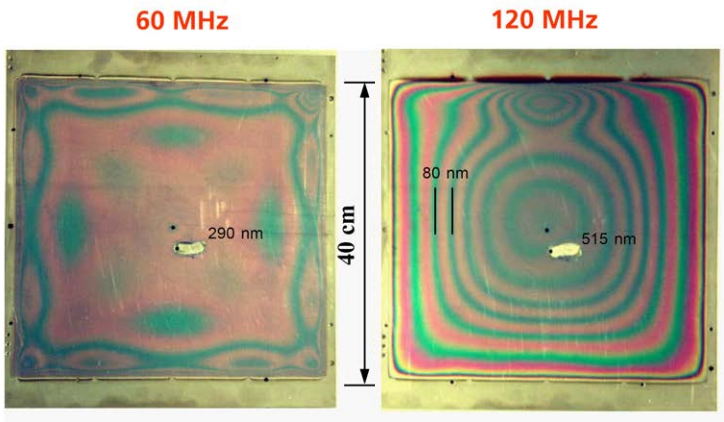


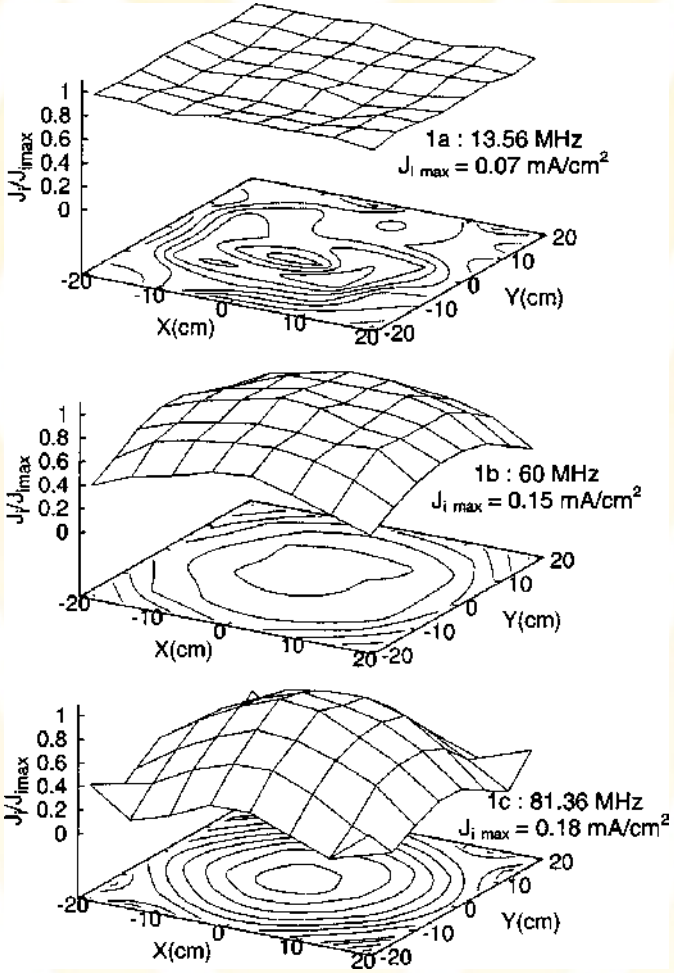
The IEDF shape can be customized by voltage waveform tailoring.

Proof-of-principle demonstration is available. Little is known about parameter scaling. Nothing is known about impact on applications.

E. Schuengel et al. 2015 Plasma Sourc. Sci. Technol. 24 045013

Uniformity control





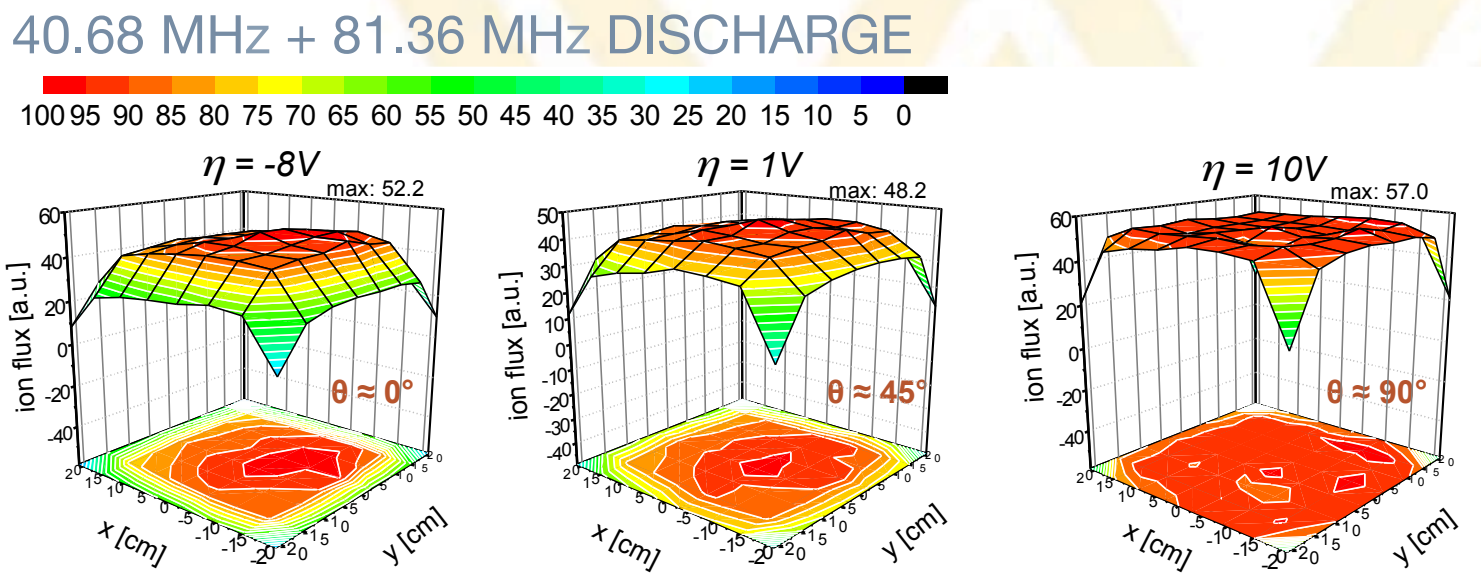
In large area CCPs, electromagnetic effects such as the Standing Wave Effect can induce lateral inhomogeneities of process relevant plasma parameters, e.g. the ion flux.

This represents a very significant problem in applications ranging from PECVD and dielectric etching to RF sputtering.

A. Perret et al. 2003 Appl. Phys. Lett. 83 243

U. Kroll et al. 1999 MRS Symp. Proc. 557 121

Uniformity Control via voltage waveform tailoring



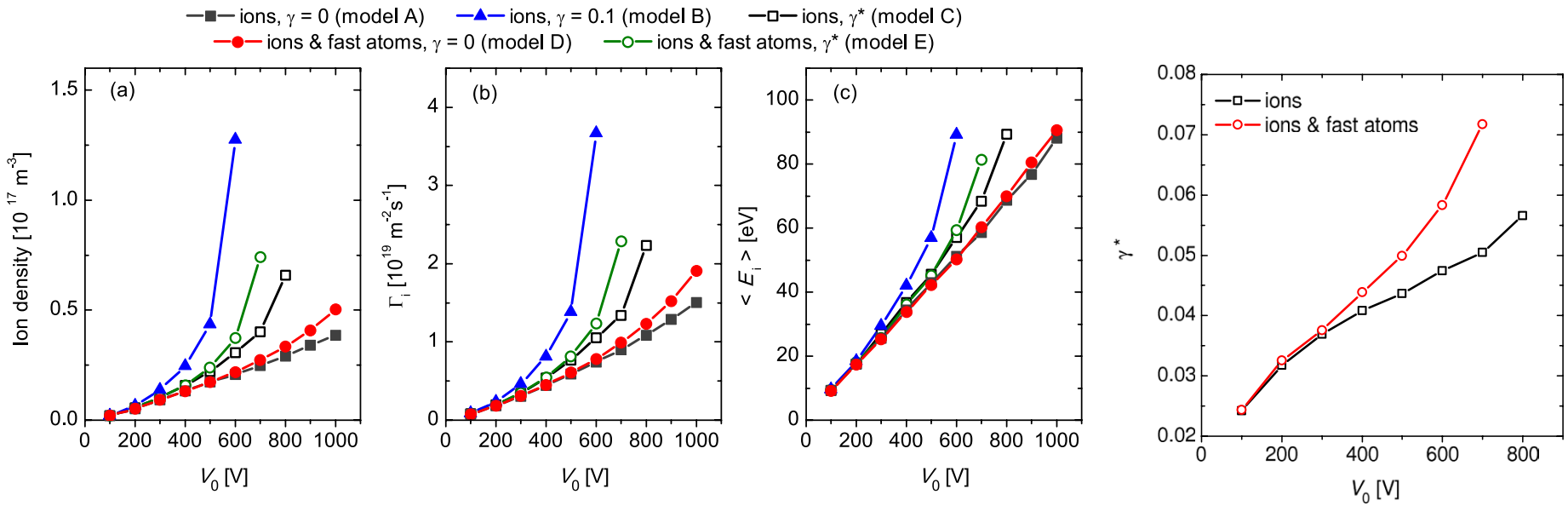
Space resolved lateral ion flux at the grounded electrode of a large area CCPs (rectangular electrodes, 40 cm x 40 cm) operated in H_2 at 150 Pa, 1.4 cm electrode gap, P_{40} = 200 W, P_{80} = 450 W.

By tuning the phase between the driving harmonics lateral non-uniformities of the ion flux due to the Standing Wave Effect can be eliminated completely.

Further research is required to explain these observations (modeling).

E. Schuengel et al. 2015 Appl. Phys. Lett. 106 054108

Realistic surface coefficients in simulations



In most simulations, surface coefficients are guessed, e.g. $\gamma = 0.1$. This can lead to drastically wrong results.

Surface coefficients typically depend on the incident particle energies, impact angle, surface material, etc.

Typically, they are only known for ultra-clean surfaces from beam experiments. The plasma, however, usually alters the surface conditions and can change the surface coefficients drastically.

Models to calculate and diagnostics to measure surface coefficients in-situ in the plasma are required.

A. Derzsi et al. 2015 PSST 24 034002

Conclusions

- Control of heating dynamics and distribution functions is an important hot topic of current research.
- A high number of important fundamental questions remains unanswered.
- Next generation plasma processing tools require process optimization based on a detailed understanding of the plasma physics rather than trial-and-error methods. Novel concepts to customize distribution functions are required.
- There is a significant lack of funding for fundamental research on particle heating dynamics and control of distribution functions in the US.
- Consequently, the US is loosing its leading role in this field to Europe and Asia. Moreover, the education of the next generation of process engineers and scientists is in great danger.
- If adequate funding is not restored, the societal and economic impact will be enormous. US companies will not be competitive in this research oriented multi-billion dollar industry.
- Collaborations between companies and academia must be strengthened. Industry and national funding agencies should provide significant levels of funding together.