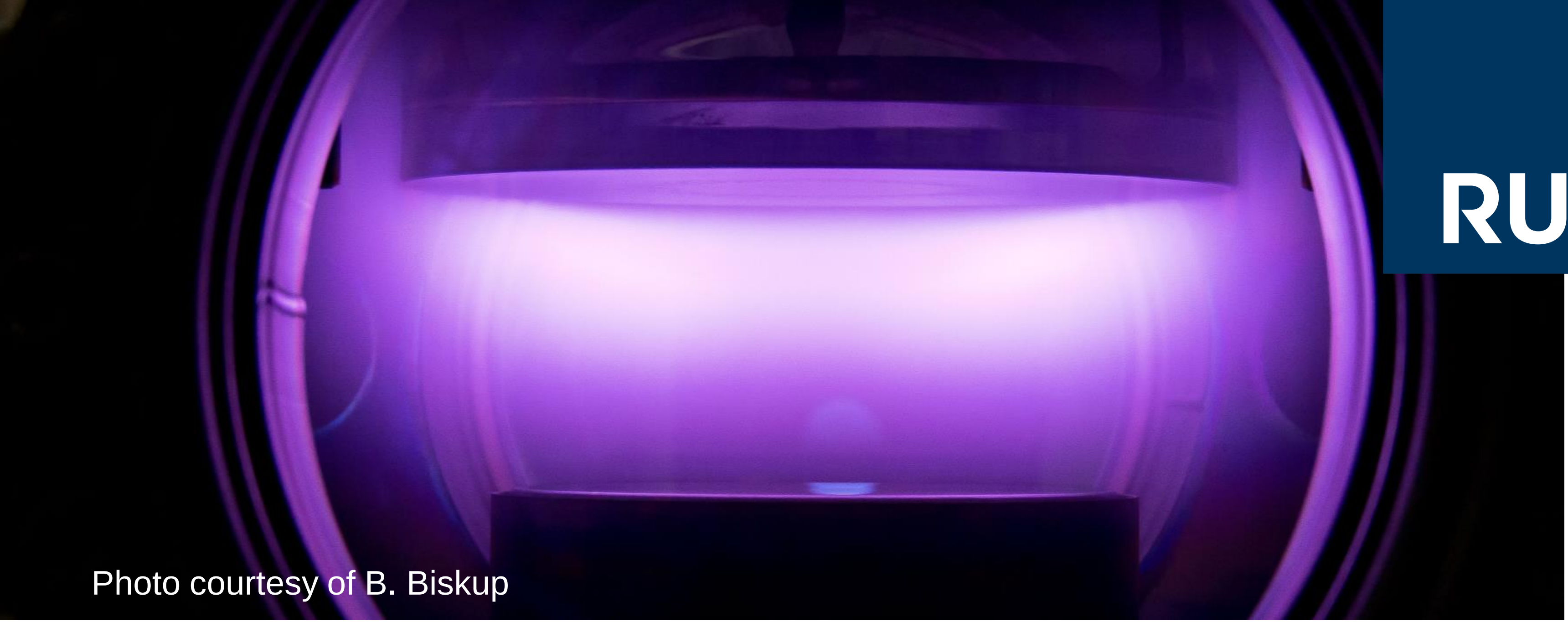

Photo courtesy of B. Biskup

RUHR-UNIVERSITÄT BOCHUM

# INDUCTIVE DISCHARGES: Past, present and future

Tsanko V. Tsankov
Institute of Experimental Physics V – Plasma and Atomic Physics
Ruhr University Bochum, Germany

# Ruhr University Bochum

**Germany in the middle of Europe and the EU**

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**Bochum in western Germany, within the Ruhr area**

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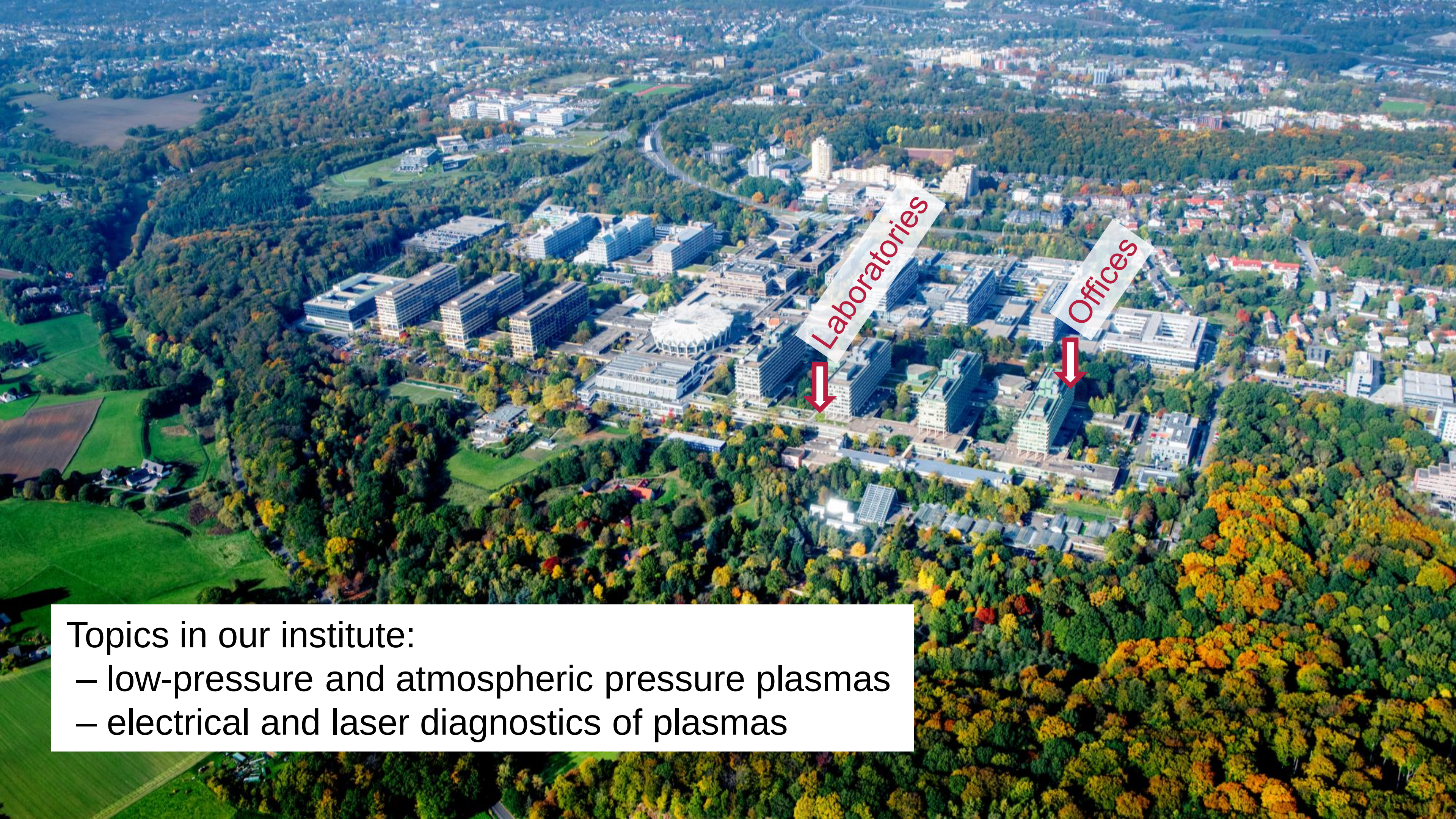

Topics in our institute:

- low-pressure and atmospheric pressure plasmas
- electrical and laser diagnostics of plasmas

# Collaborators

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Christian Lütke Stetzkamp

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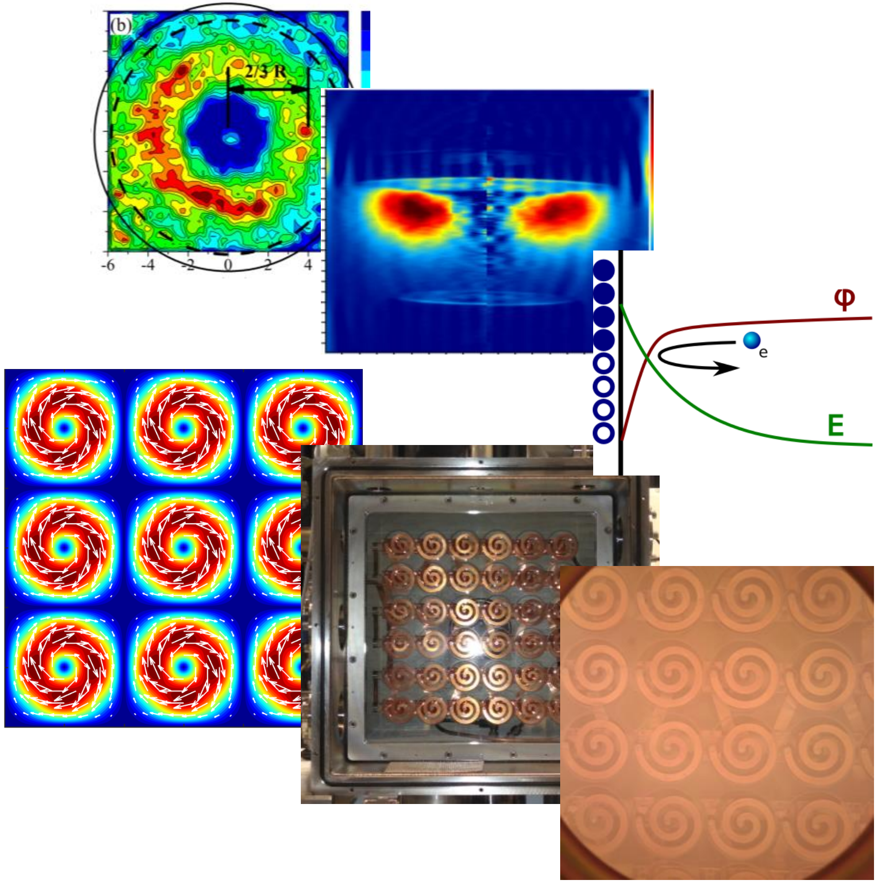
- Marc Fehling

SFB 1316

# Outline

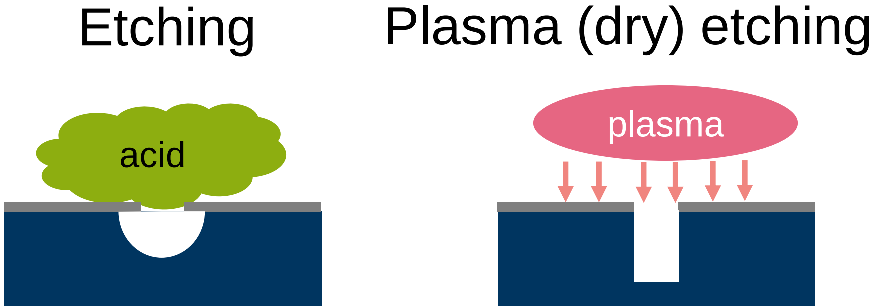
- **Introduction**
- **Classical inductive discharges**
  - **Principle of operation**
  - **Collisional (Ohmic) heating**
  - **Non-local heating**
- **Advanced concepts – INCA discharge**
  - **Principle of operation**
  - **Theoretical description**
  - **Experimental realization**
- **Summary**



# Plasma processing

- Semiconductor industry is one of the largest.
- Modern semiconductor elements require multitude of production steps.
- Etching or plasma treatment can be used.
- Plasma treatment offers
  - good selectivity
  - high degree of anisotropy
  - precision on atomic scale
- Required plasma sources:
  - high density (fast processing)
  - at low pressure (anisotropic processing).

=> Inductive discharges



# Classical inductive discharges

# Principle of operation of ICPs

- Oscillating current through a coil creates oscillating magnetic field that induces a vortex electric field.
- Inductive discharges sustain an overcritical density.

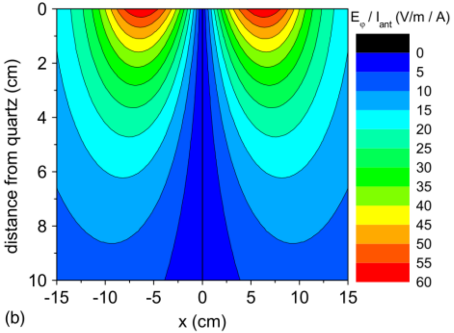
$$\omega_{pe}^2 \gg \omega_{RF}^2 \qquad \mathrm{curl}\,\vec{B} = \mu_0 \vec{j} \qquad \Delta^2 \vec{B} = \mu_0 \sigma \frac{\partial \vec{B}}{\partial t}$$

- An analytical expression for the field distribution in a homogeneous plasma can be obtained:

E-mode: I M El-Fayoumi, I R Jones and M M Turner, *J. Phys. D: Appl. Phys.* **31** (1998) 3082
H-mode: I M El-Fayoumi and I R Jones, *Plasma Sources Sci. Technol.* **7** (1998) 162

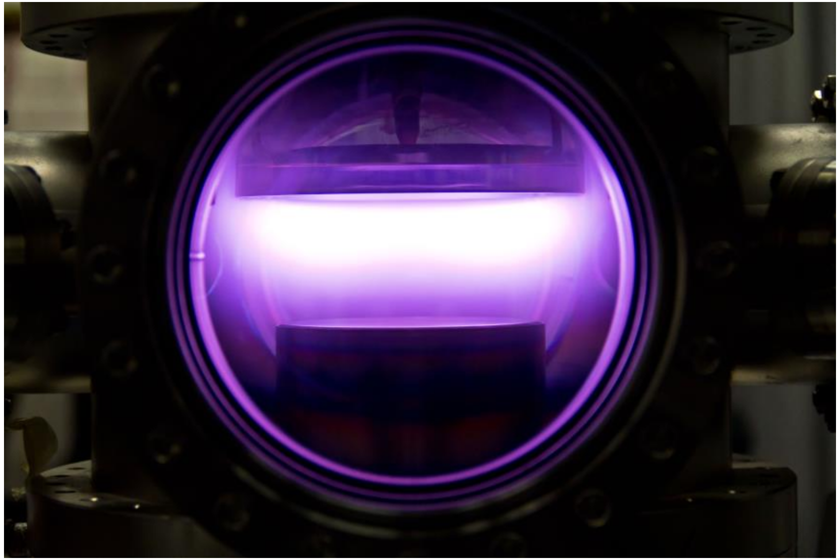
- The field is decaying (nearly) exponentially in the plasma (evanescent wave).
- The penetration depth (skin depth) depends on the plasma and the coil characteristics

$$\frac{1}{\delta^2} \sim k_{coil}^2 + \frac{\omega_{pe}^2}{c^2}$$

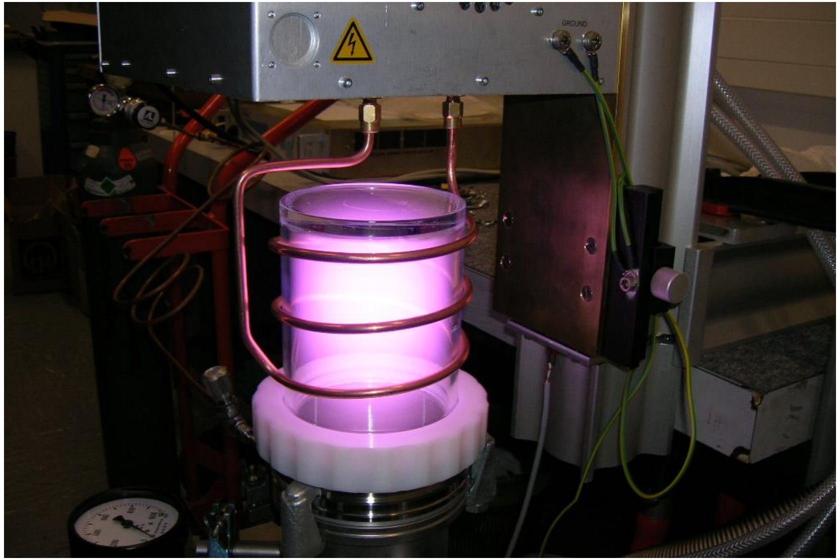


D L Crintea et al, “Phase resolved measurement of anisotropic electron velocity distribution functions in a radio-frequency discharge“, *J. Phys. D: Appl. Phys.* **41(8)** 082003 (12 March 2008), https://doi.org/10.1088/0022-3727/41/8/082003, © IOP Publishing. Reproduced with permission. All rights reserved

# Principle of operation of ICPs



**Inductive discharge with a flat antenna**
(at the top)



**Inductive discharge with a cylindrical antenna**

Photo courtesy of B. Biskup

# Principle of operation of ICPs

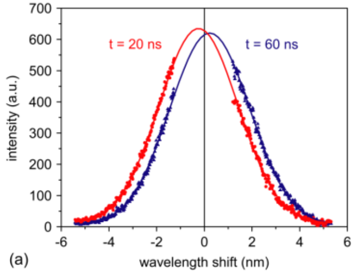
- The oscillating electric field leads to a periodic shift in the electron distribution:

$$f(\vec{v},t) = f_0(|\vec{v} - \vec{u}_{osc}(t)|) \qquad \vec{u}_{osc}(t) = -\frac{e\vec{E}_0}{m\omega}\sin\omega t$$

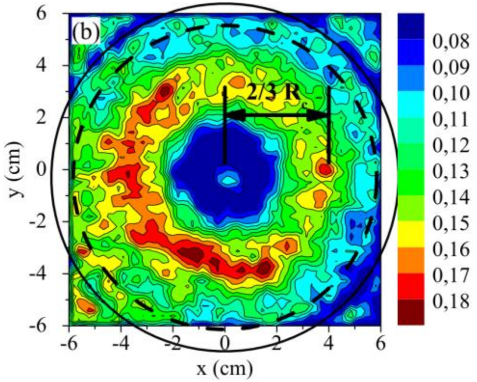
- Periodically there is an overpopulation of energetic electrons.
- The emission intensity is modulated (few percent)

$$\frac{I_{2\omega}}{\langle I\rangle} = \frac{1}{2\sqrt{1+(2\omega\tau)^2}}\left(\frac{2}{3}\frac{\varepsilon_{exc}}{k\,T_e} - 1\right)\frac{u_{osc}^2}{v_{th}^2} \propto E_0^2$$

- The electric field can be obtained from the modulation of the emission.
- Analytical prediction: field maximum is at $\mathrm{r} = \frac{2}{3}R_{coil}$

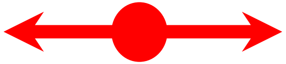


D L Crintea et al, “Phase resolved measurement of anisotropic electron velocity distribution functions in a radio-frequency discharge“, *J. Phys. D: Appl. Phys.* **41(8)** 082003 (12 March 2008), https://doi.org/10.1088/0022-3727/41/8/082003, © IOP Publishing. Reproduced with permission. All rights reserved



Ts Tsankov and U Czarnetzki, *AIP Conf. Proc.* **1390** (2011) 140

# Collisional (Ohmic) heating



- The field supplies energy to the electrons: $\frac{\partial P}{\partial V} = \langle \vec{j} \cdot \vec{E} \rangle_T$
- To obtain the energy deposition into the plasma consider the motion of the electrons in the oscillating field (**fluid description**):

$$m \frac{d\vec{u}}{dt} = -e\vec{E}_0 \cos \omega t - m\nu\vec{u}$$

- The current density is $\vec{j} = -en\vec{u} = \frac{e^2 n}{m\sqrt{\nu^2 + \omega^2}} \vec{E}_0 \cos(\omega t + \varphi)$
- There is a phase shift between the field and the current density: $\varphi = -\arctan \frac{\omega}{\nu}$
- The phase shift is important for the energy deposition:

$$\frac{\partial P}{\partial V} = \frac{1}{2} \frac{e^2 n}{m\sqrt{\nu^2 + \omega^2}} E_0^2 \cos \varphi = \frac{e^2 n}{2\,m} \frac{\nu}{\nu^2 + \omega^2} E_0^2$$

- Collisions are also important: at low pressures ($\nu^2 \ll \omega^2$) the heating increases with $\nu$

# Collisional (Ohmic) heating

- Collisions and heating are stochastic processes – **stochastic description**
- Equation of motion of the particles has a stochastic component:

$$\frac{d\vec{v}}{dt} = -\frac{e}{m}\vec{E}_0 \cos\omega t - \sum_j \Delta\,\vec{v}_j \delta(t - t_j)$$

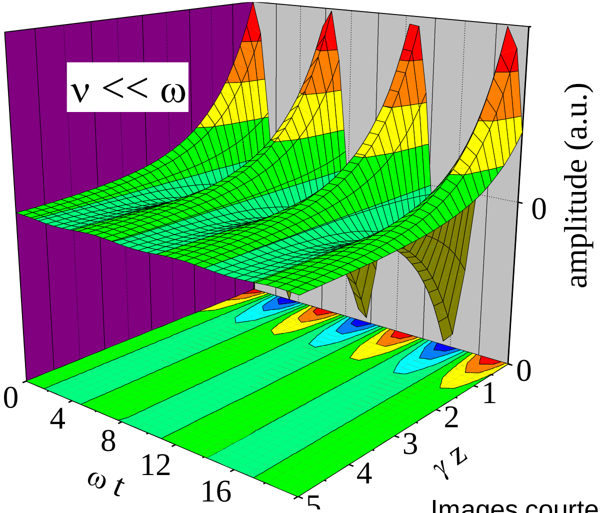
- Between two collisions the velocity of an electron changes by

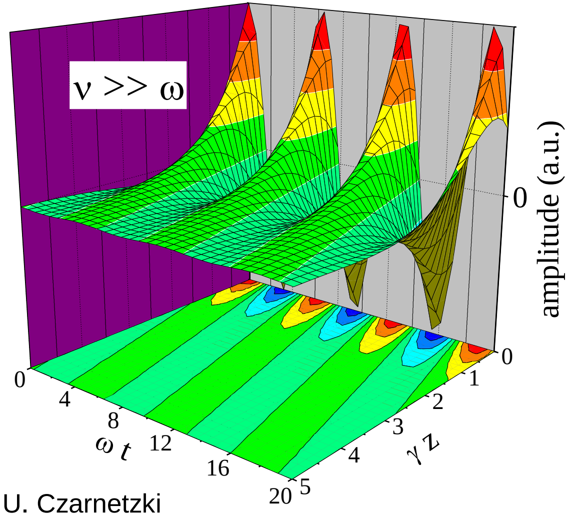
$$\Delta\vec{v} = -\frac{\mathrm{e}}{m}\frac{\vec{\mathrm{E}}_0}{\omega}\left[\sin\left(\frac{\omega\tau}{2} + \varphi\right) - \sin\left(-\frac{\omega\tau}{2} + \varphi\right)\right] \qquad \tau = t_{j+1} - t_j$$

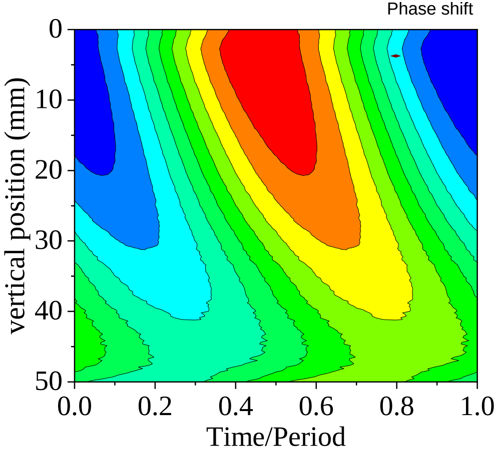
- The intervals $\tau$ between two collisions are stochastically distributed: $P(\tau) = \nu \exp(-\nu\tau)$
- The phase of the field at the time of the collision is completely random: $P(\varphi) = \frac{1}{2\pi}$
- The energy gained on average is: $\langle\Delta\varepsilon\rangle = \frac{1}{2}\langle m(\Delta\vec{v})^2\rangle_{\varphi,\tau}$
- The final result is the same: $\left\langle\frac{\partial P}{\partial V}\right\rangle = n\nu\langle\Delta\varepsilon\rangle = \frac{e^2 n}{2\,m}\frac{\nu}{\nu^2 + \omega^2}E_0^2$

# Collisional (Ohmic) heating

- The energy absorption through collisions changes the behaviour of the field in the plasma.
- Without energy absorption ($\nu \ll \omega$) the phase velocity is infinite (evanescent wave)
- With energy absorption the phase velocity is finite



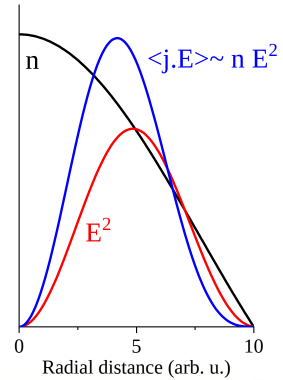


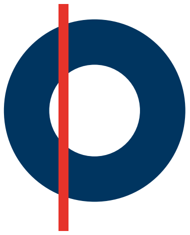


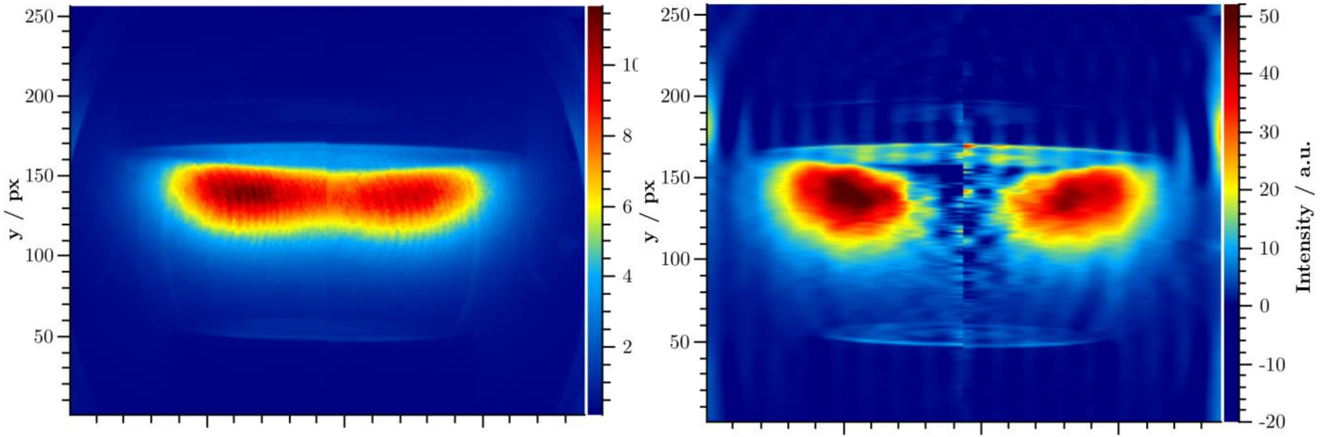
Images courtesy of U. Czarnetzki

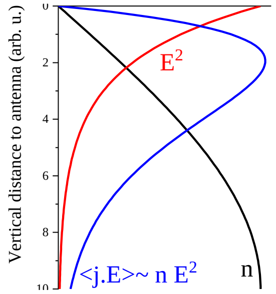
# Collisional (Ohmic) heating

- The energy deposition is proportional to $n\ E^2$ which has a torus shape.
- Can be visualized by Abel inversion of the emission at high pressure (local heating).







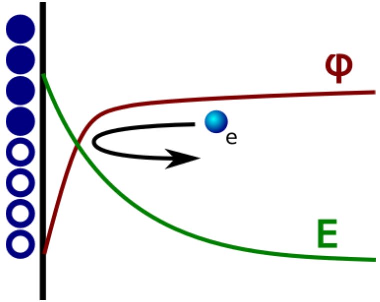


Ph Lucke, M Fehling, SOWAS student project, (2015), Ruhr University Bochum

# Non-local heating

- In ICPs the deposited energy is higher than predicted by Ohmic heating.
- Due to the thermal motion of the electrons in the inhomogeneous field, they can gain additional energy:
  - Without movement: acceleration and decceleration by the same field strength.
  - With movement: acceleration and decceleration by different field intensity.
- Description due to Lieberman and Lichtenberg

  M A Lieberman and A J Lichtenberg, *Principles of Plasma Discharges and Materials Processing,* 1st ed (1994, John Wiley & Sons, Inc.) ISBN 0-471-00577-0
- Essential aspects of the treatment:
  - Maxwellian electron distribution
  - Electrons coming from infinity with a constant velocity, reflection at $z = 0$: $z(t) = -v_{z0}|t|,\ \ v_{z0} < 0$
  - Exponential field: $\vec{E} = E_0 \cos(\omega t + \varphi)\, e^{-\frac{z}{\delta}}\, \vec{e}_x$



# Non-local heating

- Again, the velocitiy change is obtained:

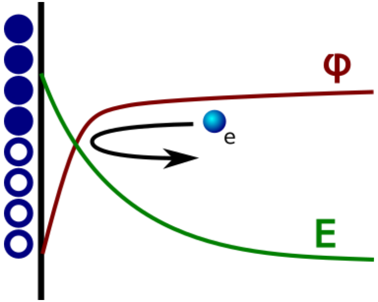
$$\Delta\vec{v} = -\frac{\mathrm{e}}{\mathrm{m}}\int_{-\infty}^{\infty}\vec{E}\,dt = \frac{eE_0\delta}{m}\frac{2v_{0z}\cos\varphi}{v_{0z}^2+\delta^2\omega^2}$$

- The energy gain is obtained from the average over all phases and the EEDF:

$$\left\langle\frac{\partial P}{\partial A}\right\rangle = -n\frac{m}{2}\langle\Delta\vec{v}^2 v_{0z}\rangle = \frac{n\,e^2E_0^2\delta}{2\,m\omega}F\left(\frac{\varepsilon_s}{k\,T_e}\right) \qquad \varepsilon_s = \frac{m}{2}(\delta\omega)^2 \qquad F(x) = \sqrt{\frac{x}{\pi}}\int_0^{\infty}\frac{\varepsilon e^{-\varepsilon}}{(x+\varepsilon)^2}d\varepsilon$$

- The result has a similar form to the Ohmic heating case:

$$\left\langle\frac{\partial P}{\partial A}\right\rangle = \left\langle\frac{\partial P}{\partial V}\right\rangle\delta = \frac{n\,e^2E_0^2\delta}{2\,m\omega}G_{Ohm}\left(\frac{\nu}{\omega}\right) \qquad G_{Ohm}(x) = \frac{x}{1+x^2}$$



- Introduction of an effective collision frequency for the stochastic heating:

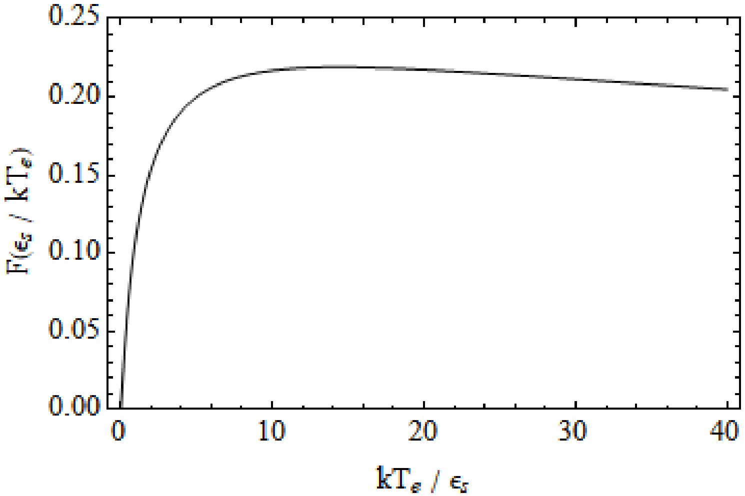
$$F\left(\frac{\varepsilon_s}{kT_e}\right) \stackrel{\text{def}}{=} G_{Ohm}\left(\frac{\nu_{stoc}}{\omega}\right)$$

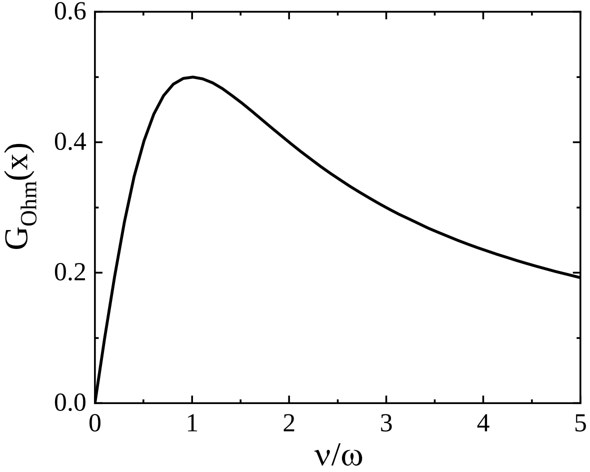
M A Lieberman and A J Lichtenberg, *Principles of Plasma Discharges and Materials Processing,* 2nd ed (2005, John Wiley & Sons, Inc.)

# Non-local heating

- The function *F* has a maximum of about 0.22 at $kT_e/\varepsilon_s \approx 14.5$.
- Possible problem is that the domains of $G_{\mathrm{Ohm}}$ and *F* do not coincide.

U Czarnetzki, *Plasma Sources Sci. Technol.* **27** (2018) 105011





- The two mechanisms can be combined in a consistent kinetic Fokker-Planck description

U Czarnetzki and L L Alves, *Rev. Modern Plasma Phys.* 2022 (accepted)

# Advanced concepts

- Short list of more intricate aspects:
  - Coupling between the stochastic and the Ohmic heating (collisions).
    U Czarnetzki and L L Alves, *Rev. Modern Plasma Phys.* 2022 (accepted)
  - Existence of "resonance conditions" ($v_{th} \approx v_{ph}$).
    U Czarnetzki, *Plasma Sources Sci. Technol.* 27 (2018) 105011

$$v_{ph} = c\frac{\omega}{\omega_{pe}}\sqrt{2}\sqrt{\frac{1+\nu^2/\omega^2}{\sqrt{1+\nu^2/\omega^2}-1}}$$

  - Non-exponential decay of the field.
    E S Weibel, *Phys. Fluids* **10** (1967) 741
    I Kaganovich, O V Polomarov, and C E Theodosiou, *Phys. Plasmas* **11** (2004) 2399
    …
  - Transversal (parallel to the coil) inhomogeneity of the field.
    U Czarnetzki, *Plasma Sources Sci. Technol.* 27 (2018) 105011 (theory)
    P Ahr, Ts V Tsankov, J Kuhfeld and U Czarnetzki, *Plasma Sources Sci. Technol.* **27** (2018) 105010 (experiment)
    …

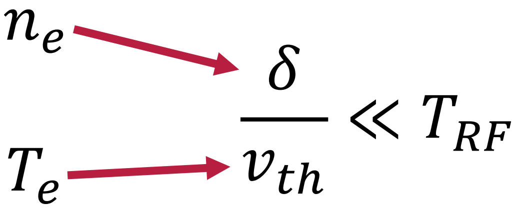
# Advanced concepts:
# INCA discharge

# Advanced concepts in ICP discharges

- Challenges for classical ICP discharges:
  - Scaling-up is problematic.
  - Stochastic heating at low pressures:
    - depends on electron density and electron temperature;
    - in the direction perpendicular to the coil;
    - works best at low RF frequencies (100 kHz to MHz).

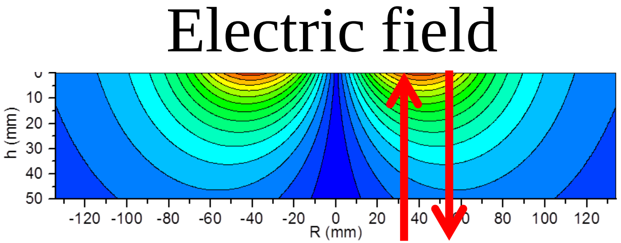
$$\frac{kT_e}{\varepsilon_s} > 10$$

Can we do better?



$$n_e \rightarrow \delta \qquad T_e \rightarrow v_{th}$$

$$\frac{\delta}{v_{th}} \ll T_{RF}$$



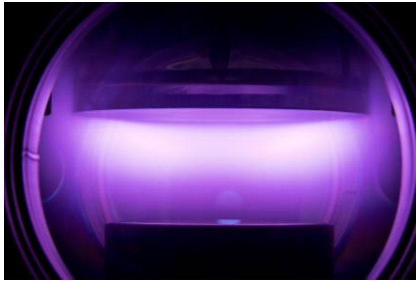
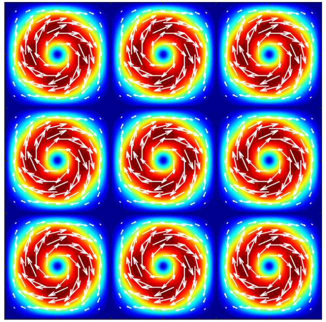
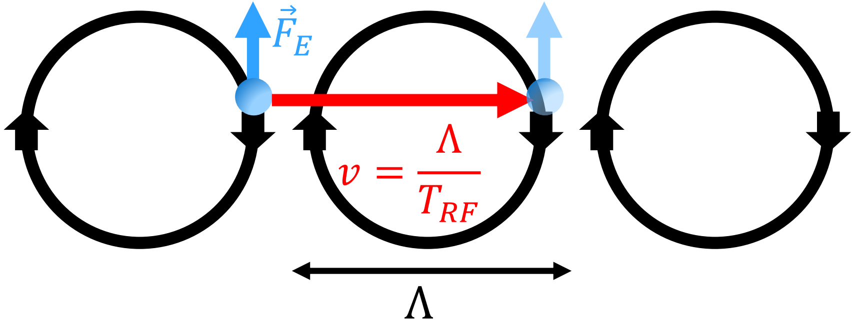


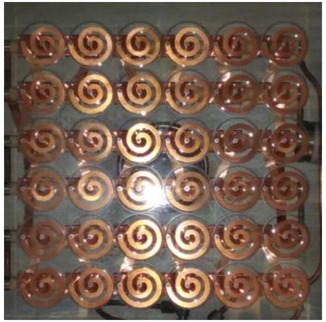
Photo courtesy of B. Biskup

# Principle of operation

- **Basic idea**: make the transversal inhomogeneity of the field periodic (period length $\Lambda$).
- Infinite 2D array of vortex fields.
- Existence of resonance velocities: $v \propto \Lambda / T_{RF}$.
- Practical realization: finite array of small, phase-correlated coils.

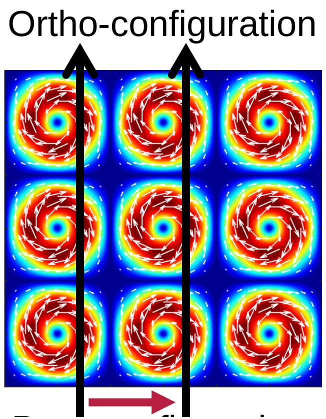


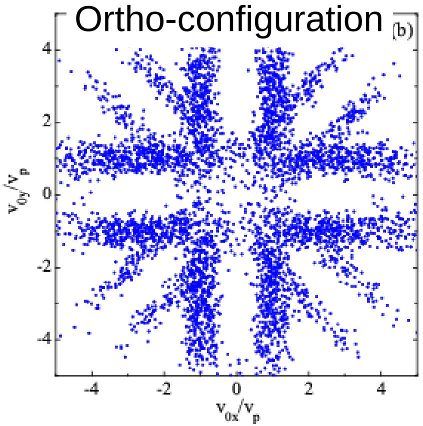




# Theoretical description

- Theoretical considerations propose two basis configurations: ortho- and para-configuration.
- Ortho-configuration: all vortices in phase.
- Para-configuration: neighboring vortices 180° out of phase.
- Resonances for the in-plane velocities: $nv_x + mv_y = v_p = \omega\Lambda/2\pi$
- For para-configuration: $n, m = \pm 1$, for ortho-configuration: $n, m = 0, \pm 1$.
- Resonances confirmed by ergodic simulations.





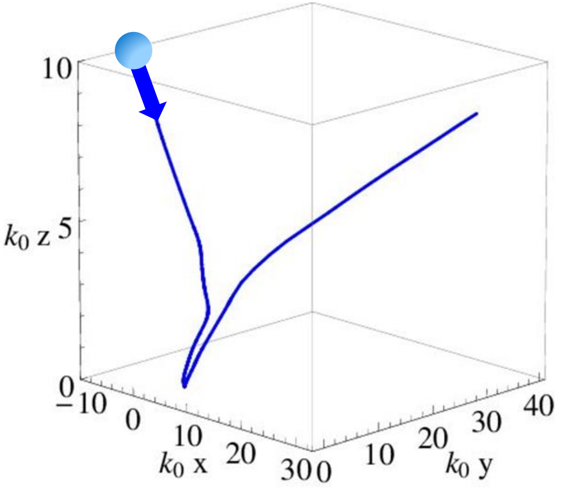
Reprinted from U. Czarnetzki, Kh. Tarnev, “Collisionless electron heating in periodic arrays of inductively coupled plasmas”, *Phys. Plasmas* **21** (2014) 123508, with the permission of AIP Publishing.

# Theoretical description: stochastic model

- Description with a Lieberman-type of model:
  - Exponentially decaying field along *z*.
  - Integration of the equation of motion.
  - Maxwellian distribution function with given electron temperature.
  - Stochastic average over 3 velocities, initial positions and time: In total 6 averages.
- Result: Analytical formula for the heating rate:

$$\left\langle \frac{\partial P}{\partial A} \right\rangle_{ortho} = \frac{n\, e^2 E_0^2 \delta}{8\sqrt{\pi}\, m\, \omega} G_{ortho}(\chi, \psi) \qquad \chi \propto \frac{v_p}{v_{th}} \propto \frac{\omega \Lambda}{\sqrt{kT_e}} \qquad \psi \propto \frac{\delta}{\Lambda}$$

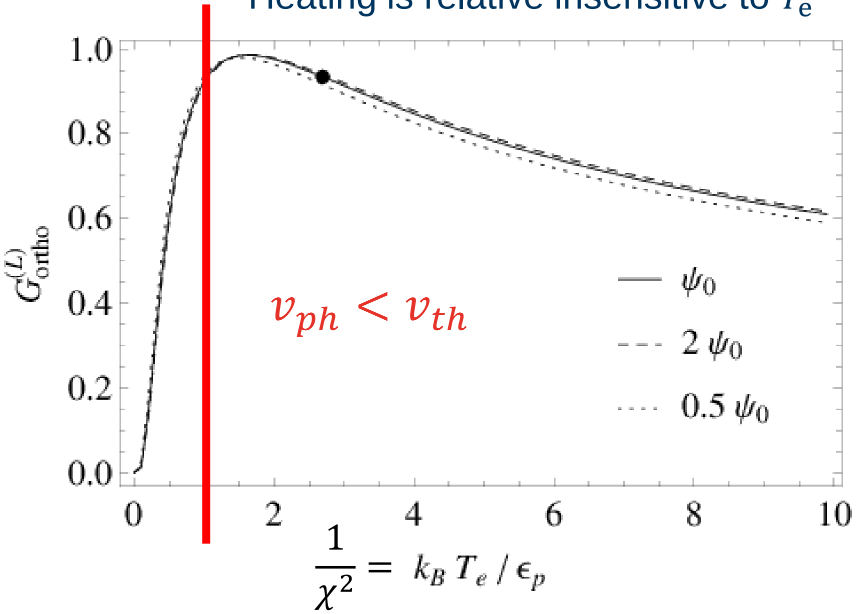
- Energy gain depends on the thermal motion through $\chi$ and on the locality through $\psi$



U Czarnetzki, “Kinetic model for stochastic heating in the INCA discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105011 (19 October 2018), https://doi.org/10.1088/1361-6595/aadeb9, © IOP Publishing. Reproduced with permission. All rights reserved

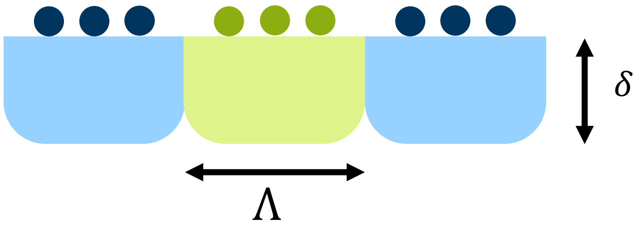
# Theoretical description: stochastic model

Heating is relative insensitive to $T_\mathrm{e}$

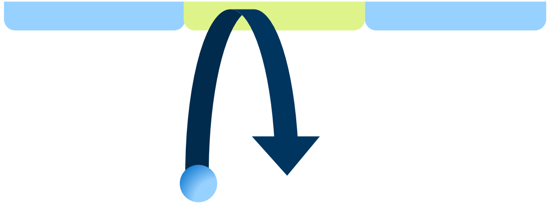


U Czarnetzki, “Kinetic model for stochastic heating in the INCA discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105011 (19 October 2018), https://doi.org/10.1088/1361-6595/aadeb9, © IOP Publishing. Reproduced with permission. All rights reserved

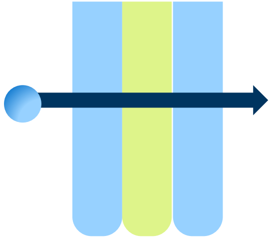
Locality parameter: $\psi = 2\pi \frac{\delta}{\Lambda}$



Classical ICP
$\psi \ll 1 \; (\delta \ll \Lambda)$



Array ICP
$\psi \gg 1 \; (\delta \gg \Lambda)$

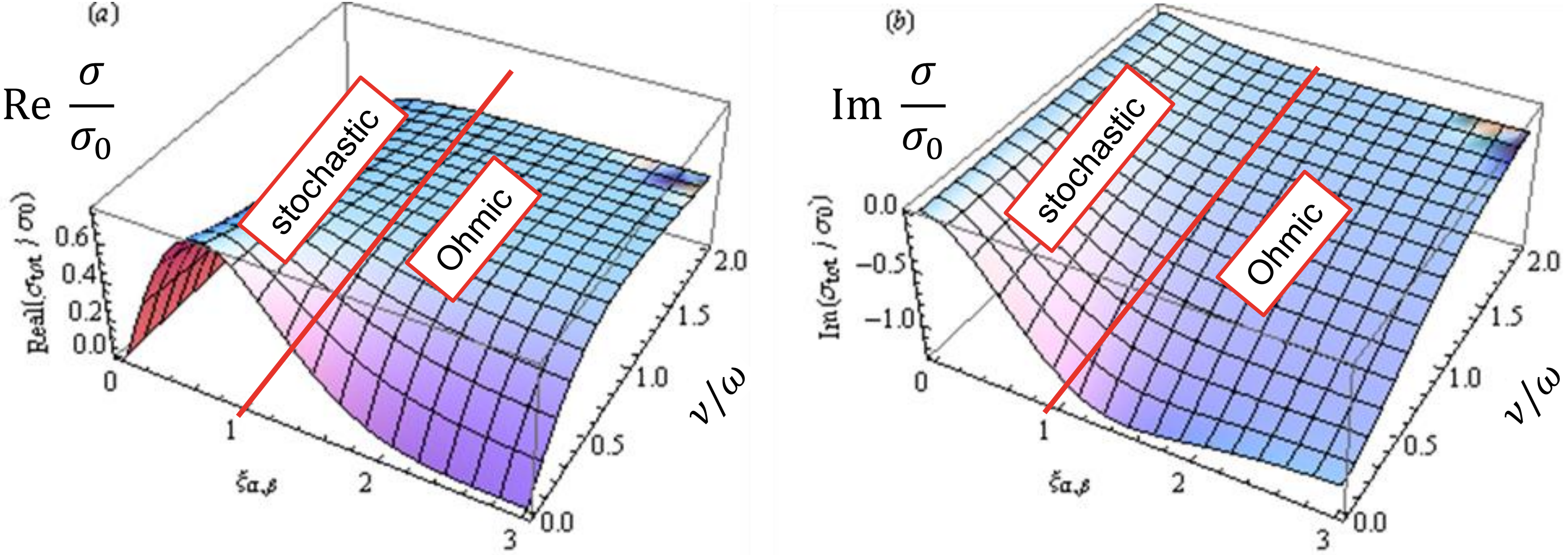


# Theoretical description: kinetic model

- Taking advantage of the vertical locality (no *z*-dependence).
- Perturbative Boltzmann model: $\frac{\partial f_1}{\partial t} + \nu f_1 + \vec{v} \cdot \nabla f_1 \approx \frac{e}{m} \vec{E} \cdot \nabla_v f_0(v)$
- Results show similarity with wave-particle interaction (Landau damping):
  - resonant energy transfer, when the electron velocity matches certain „phase velocity" $v_p = \omega\Lambda/2\pi$.
- Essential differences:
  - there is no wave: $\omega$ and $\Lambda$ are not restricted by a dispersion relation, they are externally given;
  - possibility to tailor the system parameters such that $v_{th} \sim v_p$ (optimal energy transfer);
  - energy transfer does not drive the electrons out of resonance (vortex nature of the field).

U. Czarnetzki, *Plasma Sources Sci. Technol*. **27** (2018) 105011

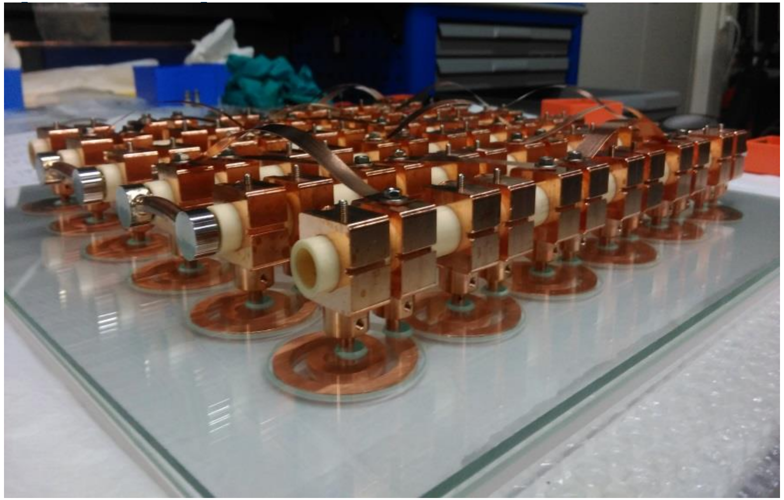
# Theoretical description: kinetic model

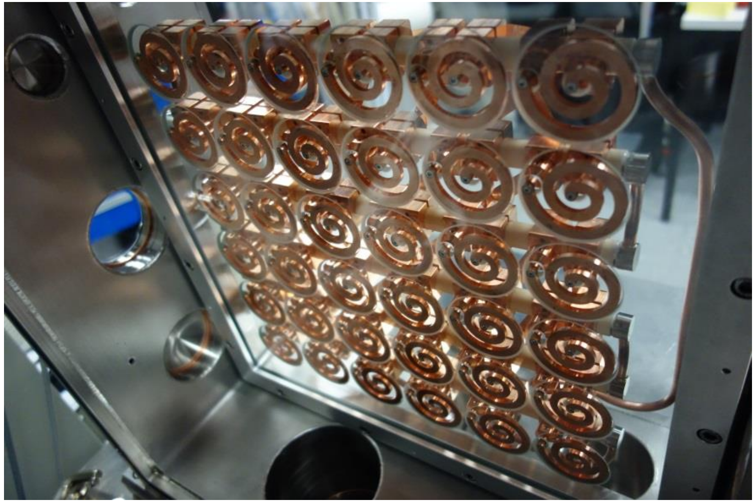


U Czarnetzki, “Kinetic model for stochastic heating in the INCA discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105011 (19 October 2018), https://doi.org/10.1088/1361-6595/aadeb9, © IOP Publishing. Reproduced with permission. All rights reserved

- Result: Complex conductivity (including collisions and stochastic effects)

# Experimental realization: Inductively Coupled Array



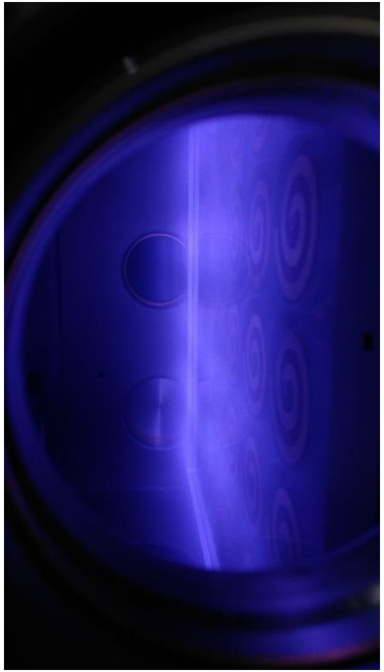


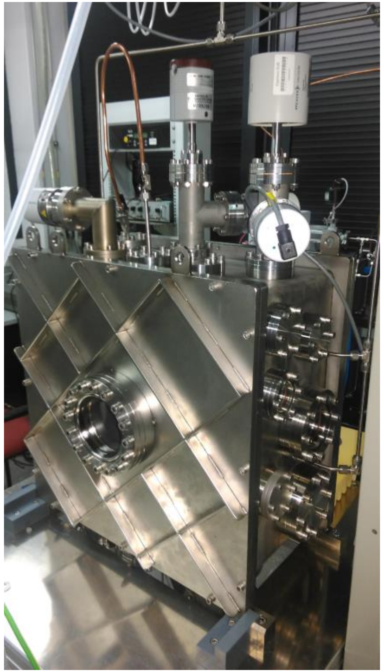
- Size 42 cm x 42 cm x 13 cm.
- 36 coils (30 cm x 30 cm).
- Ortho array (all coils in phase).

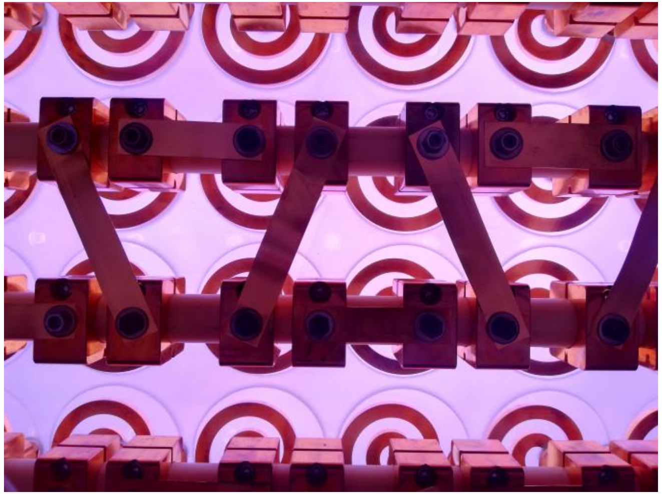
- 13.56 MHz, up to 1 kW.
- Pressure 0.1 Pa to 10 Pa.
- Para array (neighboring coils 180° phase shift).

P Ahr, Ts V Tsankov, J Kuhhfeld, U Czarnetzki, *Plasma Sources Sci. Technol.* **27** (2018) 105010

# Inductively Coupled Array (INCA)



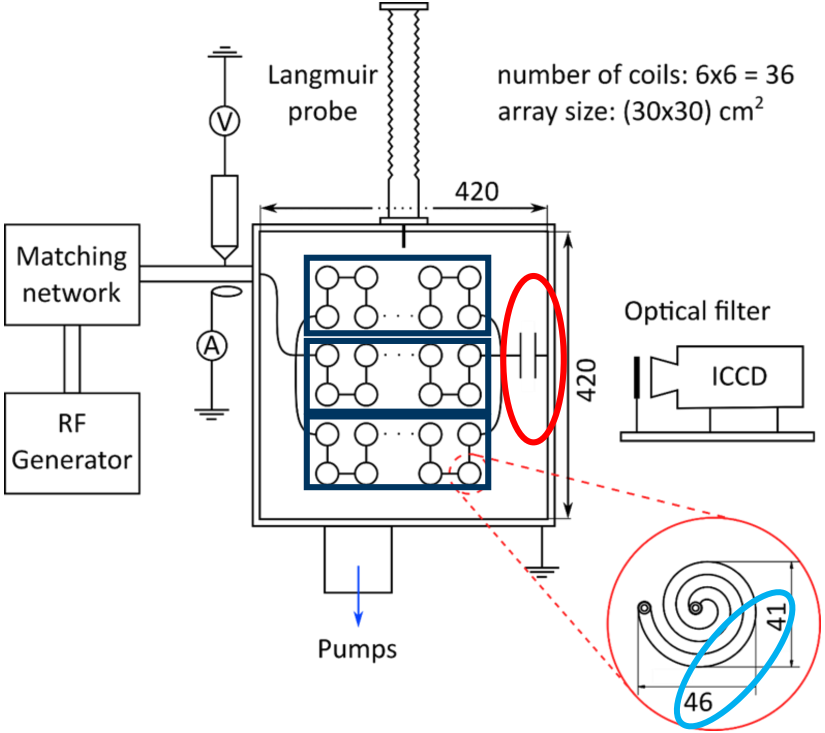




- 13.56 MHz, up to 1 kW.
- Pressure 0.1 Pa to 10 Pa.
- Efficient operation in atomic and molecular gases.

P Ahr, Ts V Tsankov, J Kuhhfeld, U Czarnetzki, *Plasma Sources Sci. Technol.* **27** (2018) 105010

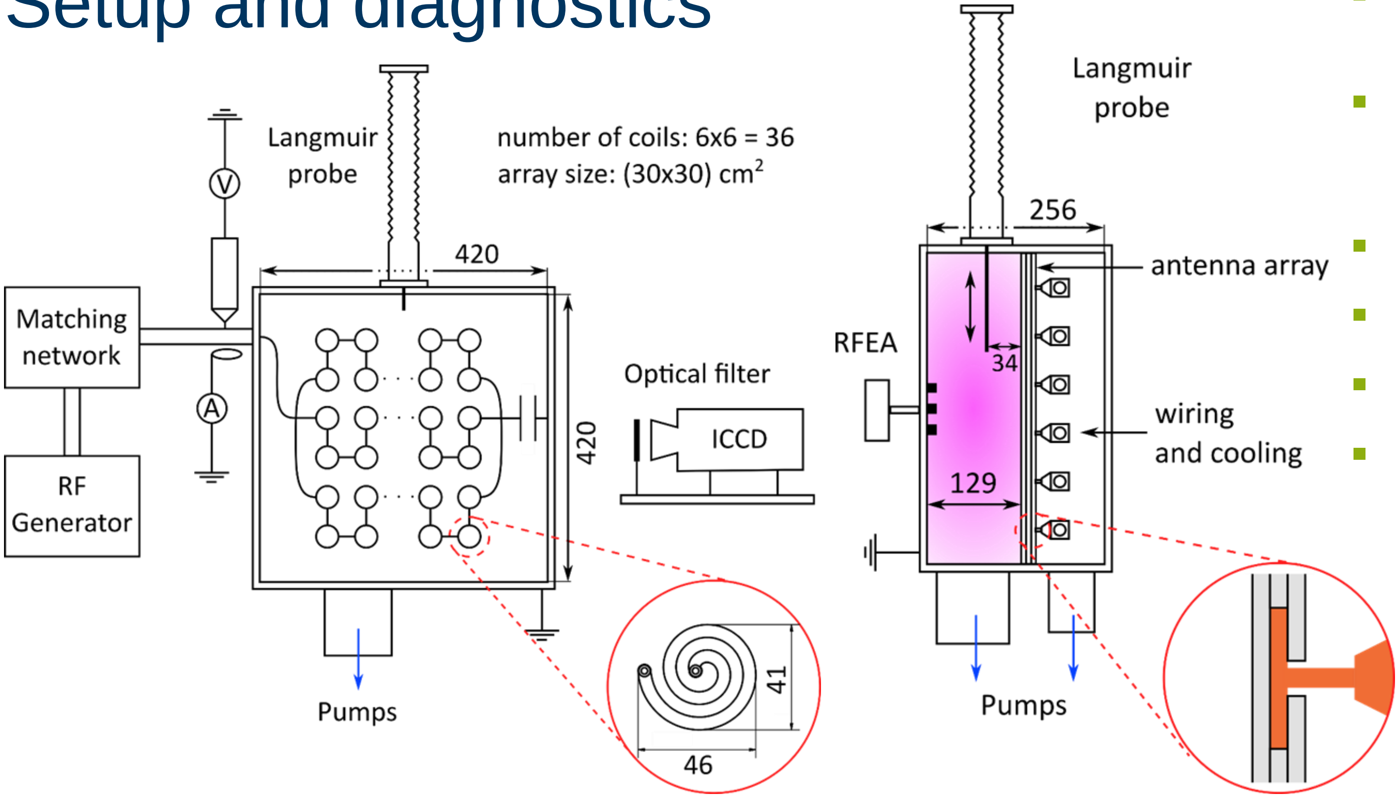
# Setup and diagnostics



- Capacitor to ground:
  - reduce capacitive coupling.
- Parallel branches of coils:
  - easy upscaling
  - same matching conditions
- Coil dimensions ($\Lambda \approx 5\ \mathrm{cm}$) optimized:
  - to match the thermal velocity of the electrons at $f = 13.56\ \mathrm{MHz}$;
  - to provide weakly collisional conditions $\lambda_{mfp} \sim \Lambda$

P Ahr, Ts V Tsankov, J Kuhhfeld, U Czarnetzki, “Inductively coupled array (INCA) discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105010 (19 October 2018), https://doi.org/10.1088/1361-6595/aadb69, © IOP Publishing. Reproduced with permission. All rights reserved

# Setup and diagnostics



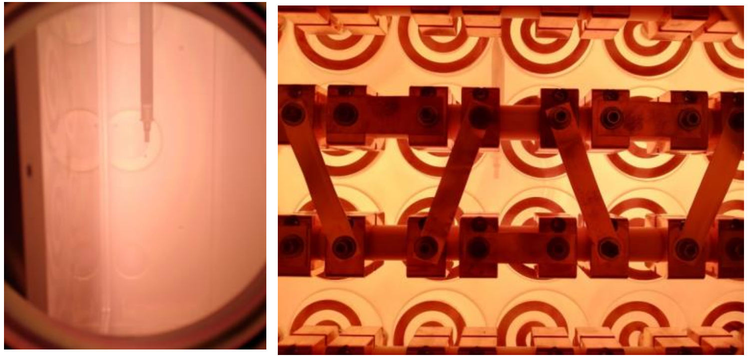
- B-dot probe: E-field configuration
- Langmuir probe: spatially resolved EEPF, Vpl
- RFEA: IVDF
- ICCD: RF-MOS
- Spectrometer: OES
- Voltage and current probes

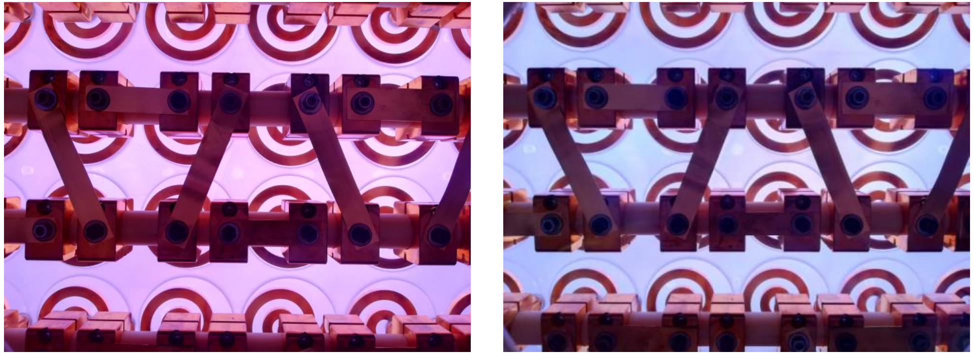
P Ahr, Ts V Tsankov, J Kuhhfeld, U Czarnetzki, “Inductively coupled array (INCA) discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105010 (19 October 2018), https://doi.org/10.1088/1361-6595/aadb69, © IOP Publishing. Reproduced with permission. All rights reserved

# Operation in different gases

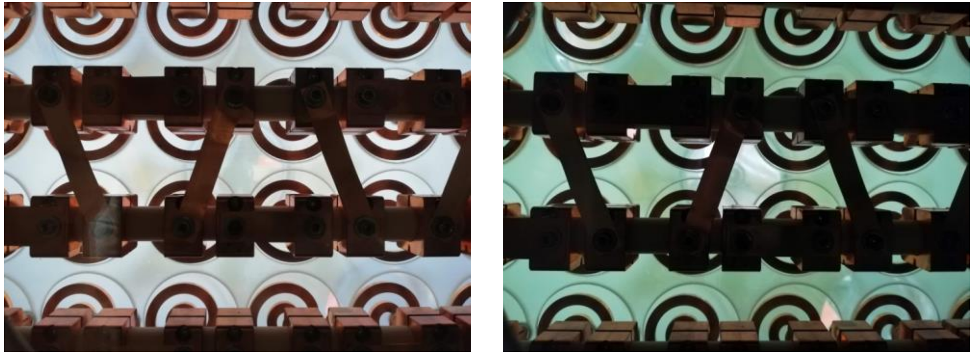
**Neon (Ne)**

**Nitrogen ($N_2$)**



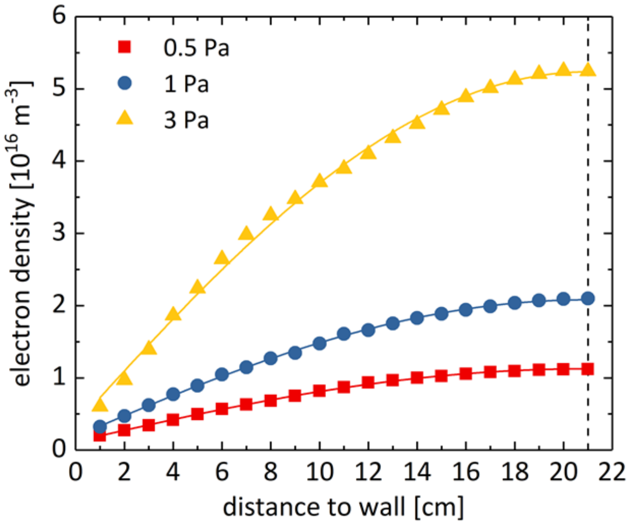


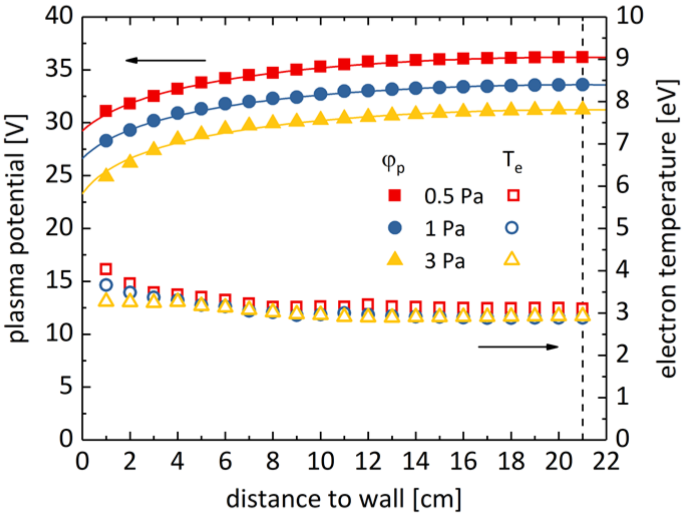
**Argon (Ar)**



**Oxygen ($O_2$)**

# Spatial plasma parameter profiles (Argon, 300 W)

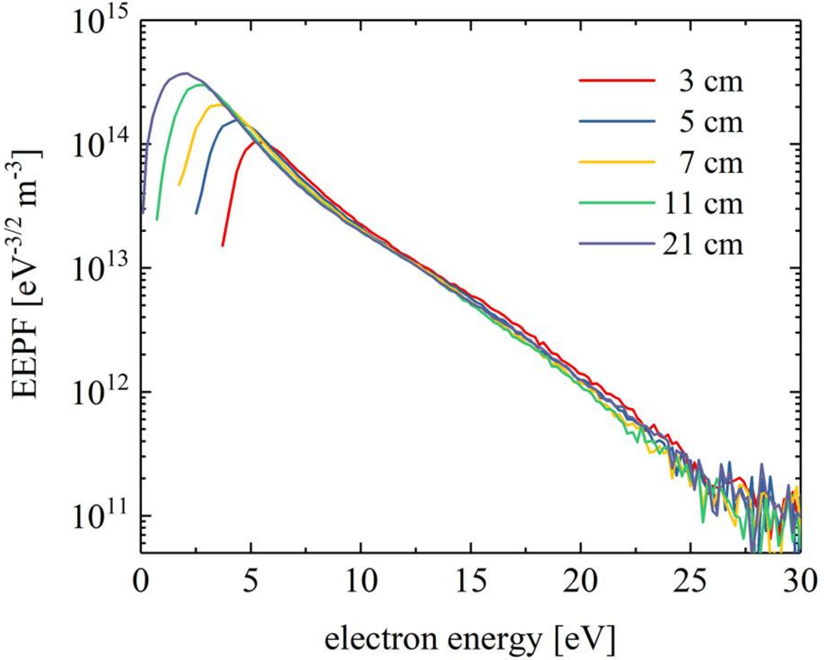




- Perfect diffusion (cosine) profile
- Consistency between $n_e(x)$ and $V_{pl}(x)$ profiles in the bulk

P Ahr, Ts V Tsankov, J Kuhhfeld, U Czarnetzki, “Inductively coupled array (INCA) discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105010 (19 October 2018), https://doi.org/10.1088/1361-6595/aadb69, © IOP Publishing. Reproduced with permission. All rights reserved

# Non-locality of the EEPF (Argon, 0.5 Pa, 300 W)



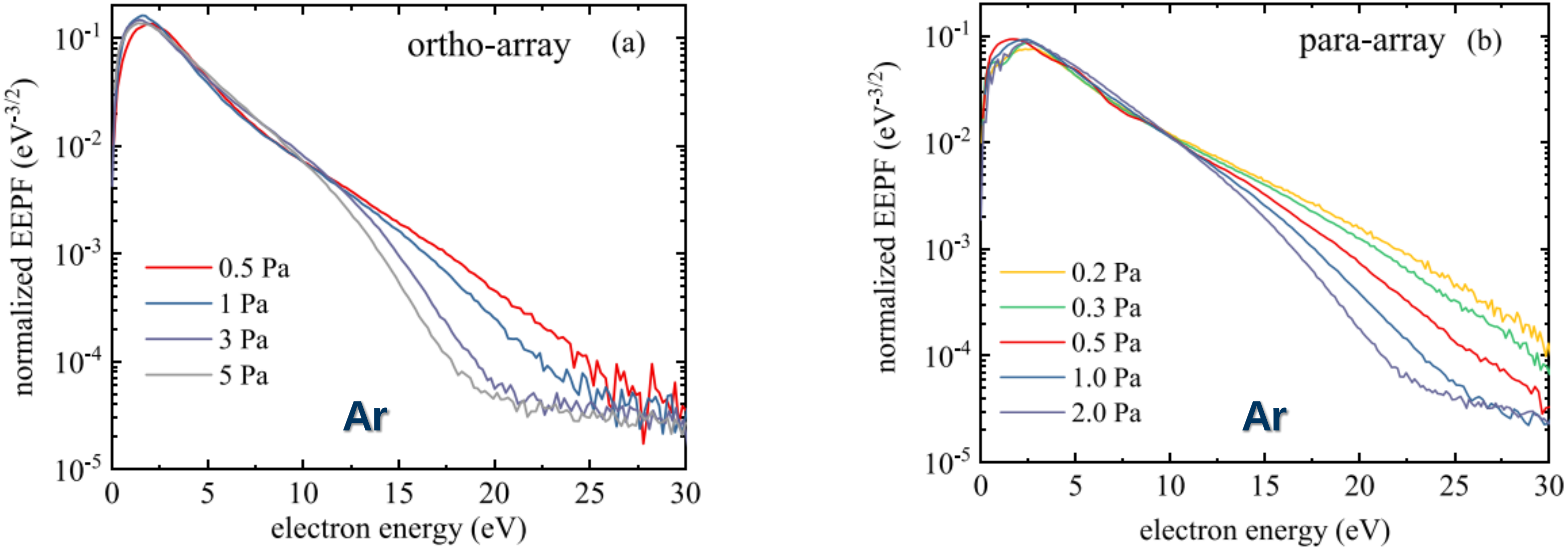
- Spatially resolved EEPF measurement.
- EEPFs shifted by the local plasma potential:

$$f(x,\varepsilon) = f(\varepsilon - e\varphi(x))$$

- Perfect overlap: Non-local distribution function.

P Ahr, Ts V Tsankov, J Kuhhfeld, U Czarnetzki, “Inductively coupled array (INCA) discharge”, *Plasma Sources Sci. Technol.* **27(10)** 105010 (19 October 2018), https://doi.org/10.1088/1361-6595/aadb69, © IOP Publishing. Reproduced with permission. All rights reserved

# Maxwellization of the distribution functions

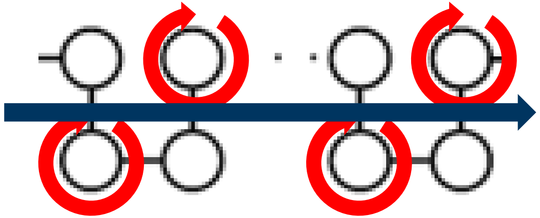


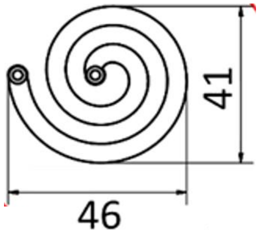
C Lütke Stetzkamp, Ts V Tsankov, U Czarnetzki, “Operation of the inductively coupled array (INCA) discharge as a para-array”, *J. Phys. D: Appl. Phys.* **54(38)** 385204 (7 July 2021), https://doi.org/10.1088/1361-6463/ac0c4b, © IOP Publishing. Reproduced with permission. All rights reserved

- Transition to Maxwellian distribution when stochastic heating becomes dominant (electron mean free path > cell size).
- Only confined electrons are measured due to finite dynamic range of the Langmuir probe.

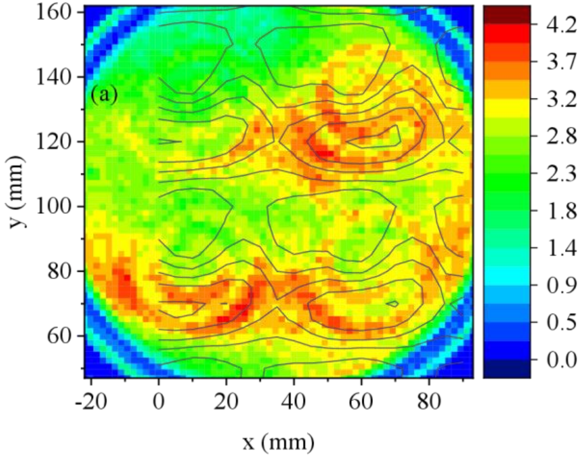
# Structure of the electric field

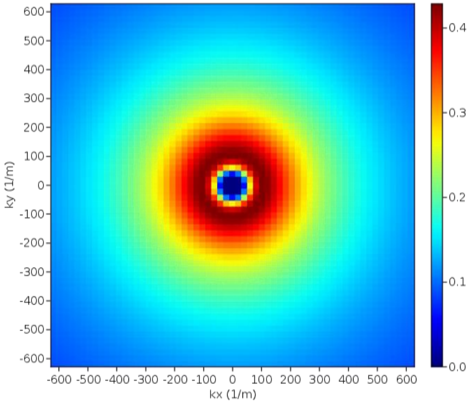
- Deviations are observed between the expected and the experimentally realized field configuration.
- Theoretical calculations show:
  - This is an effect of the coil wiring.
  - It has no influence on the energy coupling (long-range structure).



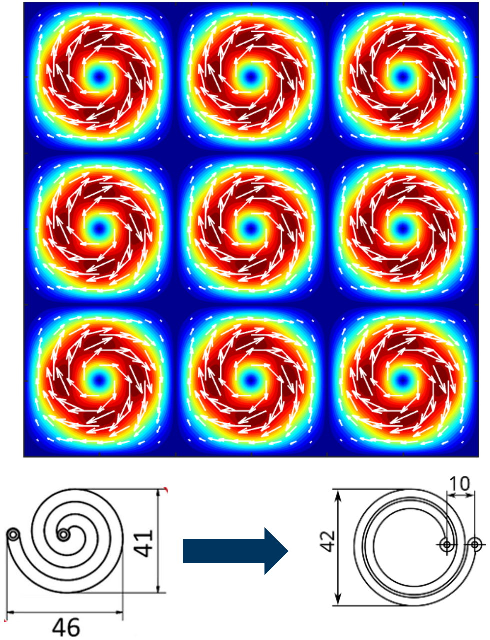


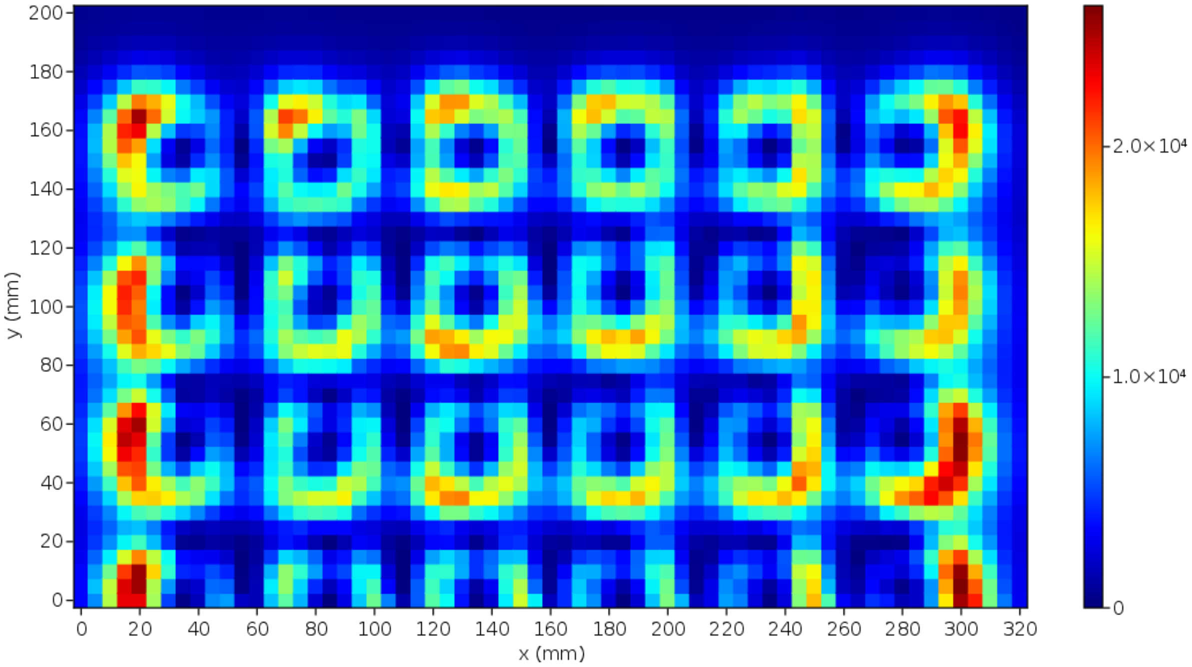
$$\left\langle \frac{\partial P}{\partial A}\right\rangle = \frac{n\, e^2 \delta}{8\sqrt{\pi}\, m}\,\frac{\omega_0}{\omega}\,\frac{1}{A}\int d^2k_\perp \hat{E}^2(\vec{k}_\perp, z=0)\,\frac{\omega_0}{v_{th}k_\perp}\exp\left(-\frac{\omega_0^2}{v_{th}^2 k_\perp^2}\right)$$





# Structure of the electric field

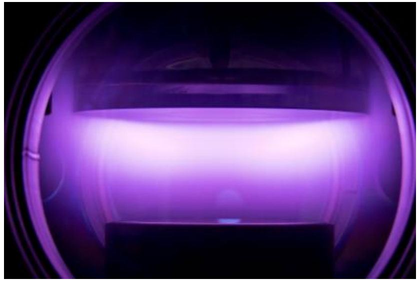


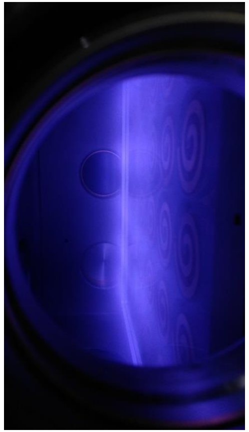


- New generation of coils brings the experimental field even closer to the theoretical one.

# Summary

Photo courtesy of B. Biskup

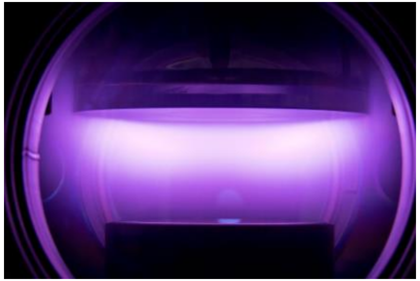




- The mechanisms of energy coupling in inductive discharges enable plasma operation also in nearly collisionless conditions.
- Different approaches exist for the description of these mechanisms.
- These approaches provide straightforward application to more advanced scenarios, like the periodically structured fields in INCA.
- These vortex fields provide a non-local collisionless heating mechanism for electrons and can be arbitrarily designed for optimal energy efficiency.
- In an optimized array, heating depends only weakly on the electron temperature.
- This new heating concept has been realized in an experiment and investigated theoretically.
- Reliable operation with various gases and under broad range of conditions is possible.
- Extension to large areas of $m^2$ size is straightforward.

# Thank you!

Photo courtesy of B. Biskup



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