Self-organization in ExB discharges

André Anders, Lawrence Berkeley National Laboratory……

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Mark A. Cappelli…

J…

M…

Ma… ……

Mic… Univ. California at Berkeley….

Yevgeny Raitses, Princeton Plasma Physics Laboratory……

David N. Ruzic, University of Illinois at Urbana-Champaign

…and there are other White Papers touching on the subject, incl. but not limited to those by

- Smolyakov et al.
- Shneider et al.
- Godyak et al.
- Raitses et al.
- …

The ExB Research Frontier: 90 Years of Progress

sheath ⟷ meets ⟷ closed electron drift

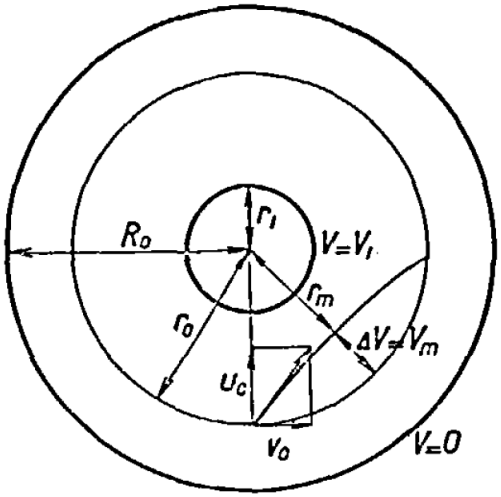


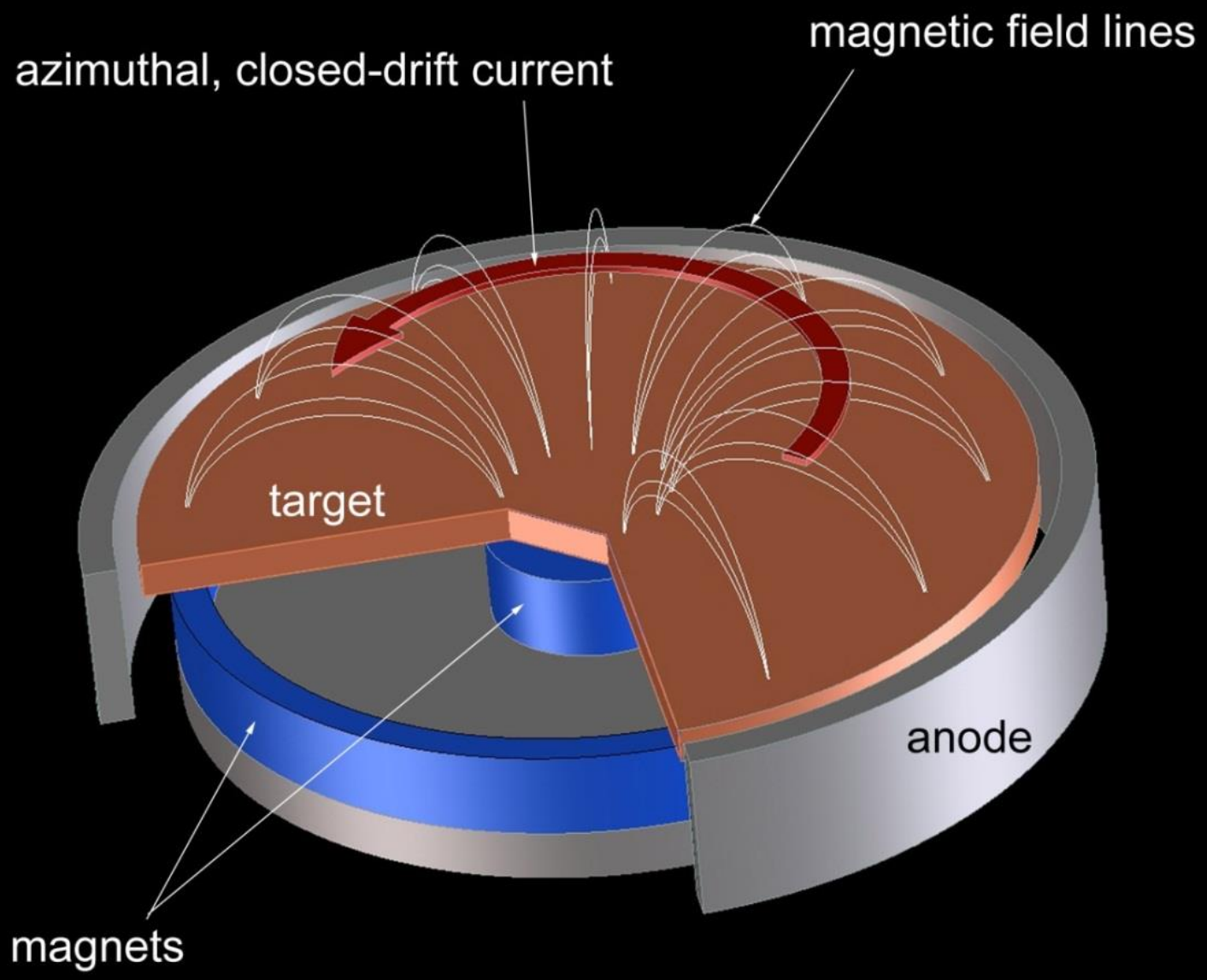
Fig. 2. Bezeichnungen zur Beschreibung der Elektronenbewegung im Magnetfeld.

I. Langmuir, K.B. Blodgett, Phys. Rev. 22 (1923) 347.

F.M. Penning, Physica 3 (1936) 873.

→ basis for many applications, in particle traps, Hall thrusters, plasma& ion sources, magnetrons, ExB micro-discharges, ...

→ surprisingly, a detailed, deep understanding is still lacking as there are plasma instabilities, self-organization, and chaos

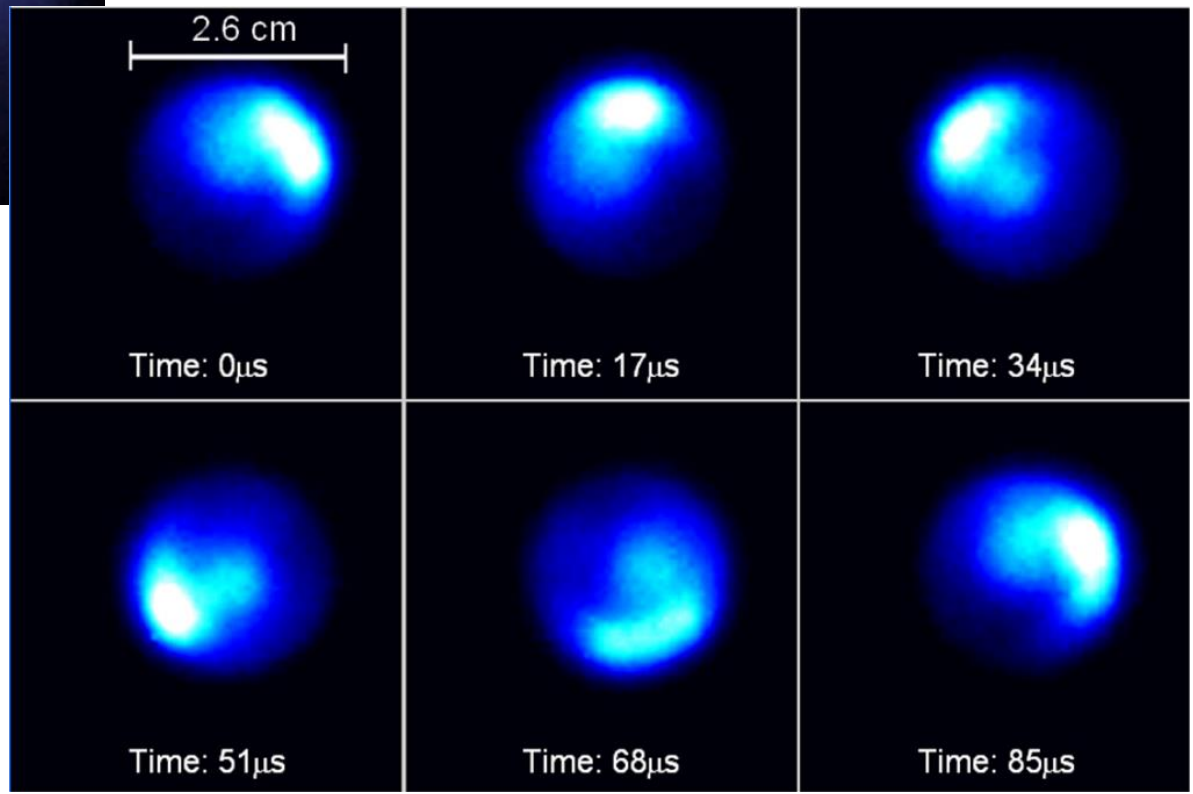


ExB drift and sheath coupling can be used to trap electrons, in a first approximation
→ plasma can be produced at very low pressure

A. Anders, Surf. Coat. Technol. **205** (2011) S1.

Self-Organization and Particle Transport in Hall Thrusters

- In Hall Thrusters, basis of plasma propulsion, ExB accelerates ions.
- Azimuthal spokes are rotating, self-organized plasmoids of high n_e & T_e.



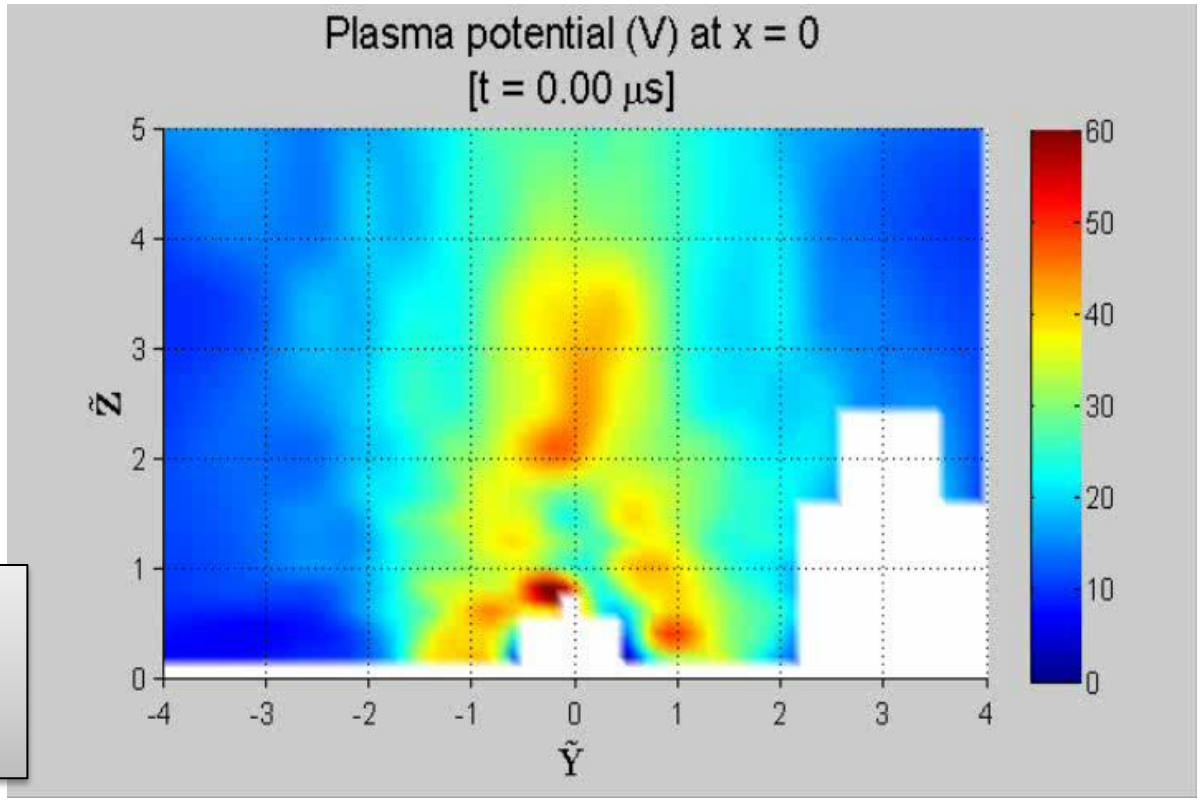
C.L. Ellison, Y. Raitses, N.J. Fisch, Phys. Plasmas **19** (2012) 013503.

J. Parker, Y. Raitses, N. J. Fisch, Appl. Phys. Lett. **97** (2010) 091501 .

Thrusters

- Low frequency ionization instability impacts performance
  - Ions ejected in bursts (detected by LIF, probes), with multiple velocity classes emerging at various times in the discharge current cycle
- Complex spatial-temporal structure derived from potential probes

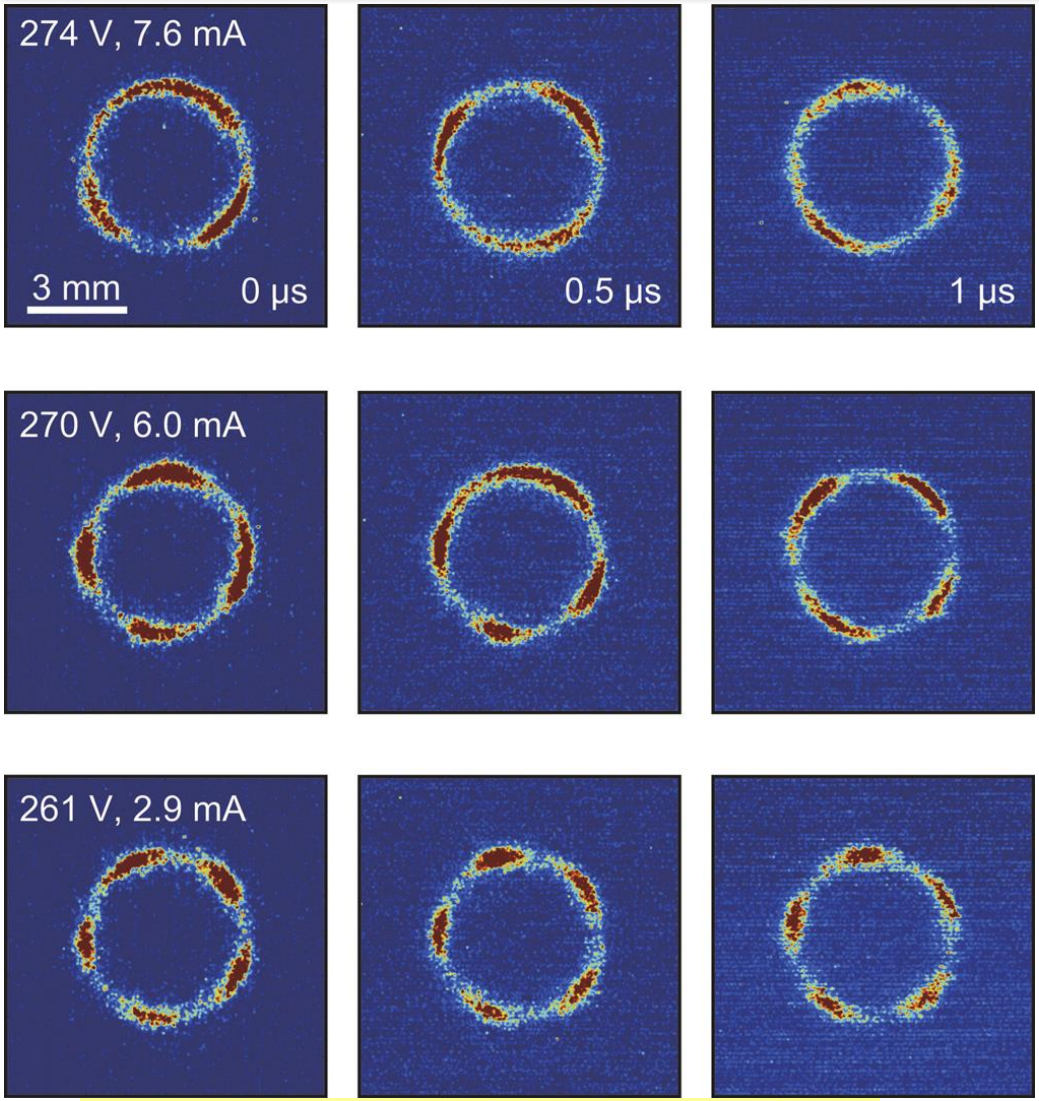
BHT-200 plasma thruster



Movie of plasma potential in the plume depicts complex rotating helical structures.

A. W. Smith and M. A. Cappelli Phys. Plasmas **16**, 073504 (2009), C. V. Young *et al*, Appl. Phys. Lett. **106**, 044102 (2015)

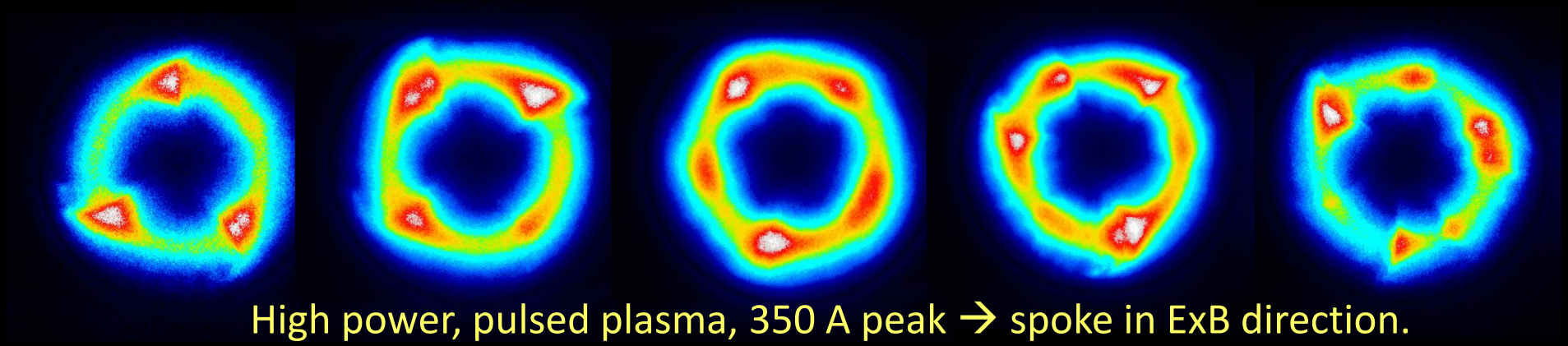
ExB Micro-Discharges



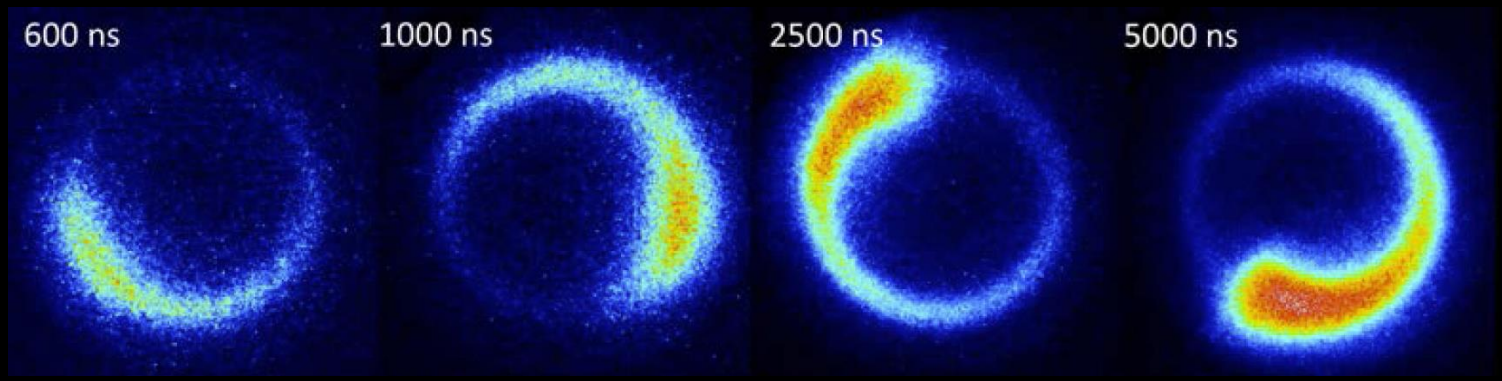
T. Ito, C.V. Young, M.A. Cappelli, Appl. Phys. Lett. **106** (2015) 254104.

- 150 mTorr Ar ExB plasma magnetron
- Waves (m = 3–5) are propagating clockwise, opposite the ExB direction.

Self-organization and Turbulence, Chaos



High power, pulsed plasma, 350 A peak → spoke in ExB direction.



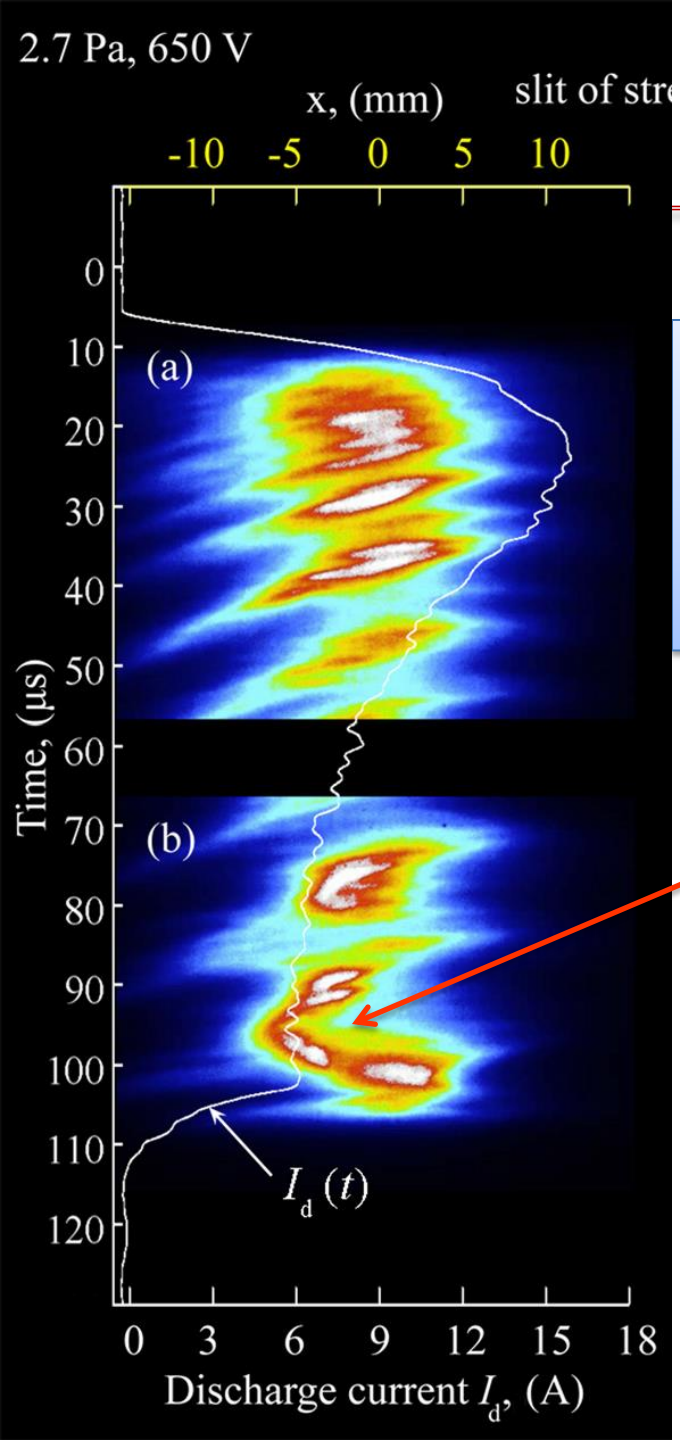
Very low power, dc plasma, 4 mA →spoke in - ExB direction.

Similarities and differences suggest that structures

- show interaction (self-self-organization)
- show changes, evolution, turbulence, chaos

A. Anders, *et al.*, J. Appl. Phys. **111** (2012) 053304, A. Anders, et al., IEEE Trans. Plasma Sci. **42** (2014) 2578.

Competing Processes

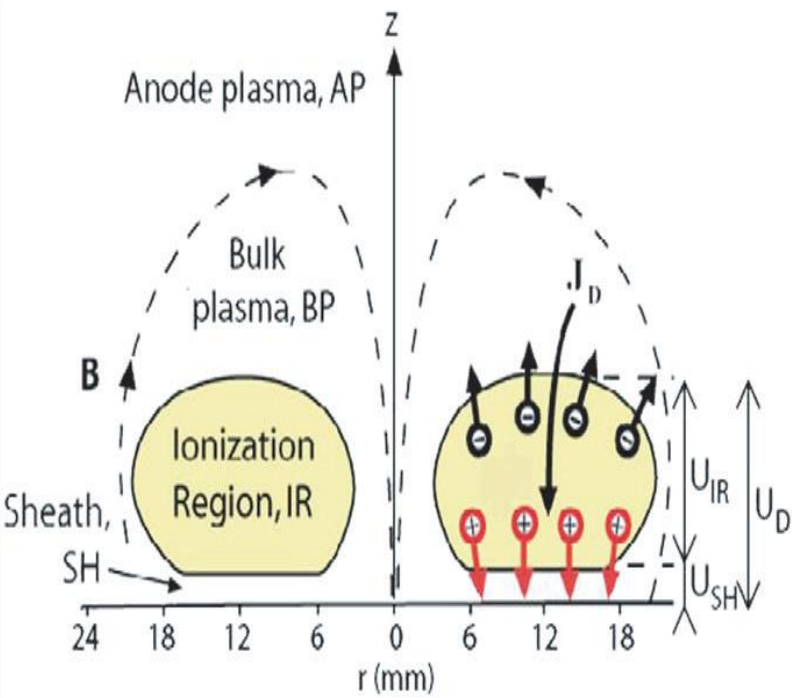


Complex, non-linear, and competing processes:
e.g. Ionization zones or "spokes" change direction when changing power density

Y. Yang, J. Liu, L. Liu, A. Anders, Appl. Phys. Lett. **105** (2014) 254101.

Challenges in Theory & Simulation

- non-uniform plasmas; plasma density can vary by several orders of magnitude
- very different time scales are involved (ps to ms)
- state-of-the art" often strong, sometimes over-simplifying assumptions
  - such as azimuthal symmetry, which a priori prohibits the study of instabilities in that dimension
  - models using a conceptual structuring of the plasma in distinct regions give some insight in the physics but do not fully capture transport properties associated with instabilities.



C. Huo, *et al.*, Plasma Sources Sci. Technol. **22** (2013) 045005.

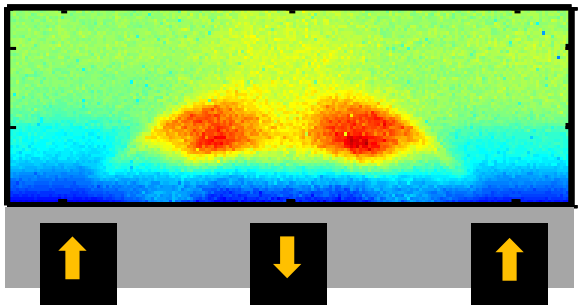
Challenges in Theory & Simulation

- **Particle-in-Cell (PIC)**: Show onset and evolution of instabilities but are challenged by locally high plasma density and dynamics, ultimately 3D phenomena. To date, PIC addresses only lowest plasma density (low-power dc).
- **Fluid-hydrodynamics:** Difficulty in addressing these devices. The magnetic fields are highly non-uniform having magnitudes of a few Gauss to many kG, which makes guiding center approximations inappropriate.
- **New modeling techniques** need to be developed for both PIC and fluid approaches, as total simulation times of ~100 μs to many ms are a huge challenge, even when using high-performance-computing platforms.
- Problems will need **high-performance computing** but likely cannot be solved by simply using more processors – modern high-fidelity algorithms are required.
- Methods combining theory and numerical analysis need to be developed, followed careful **verification and validation of simulations**.

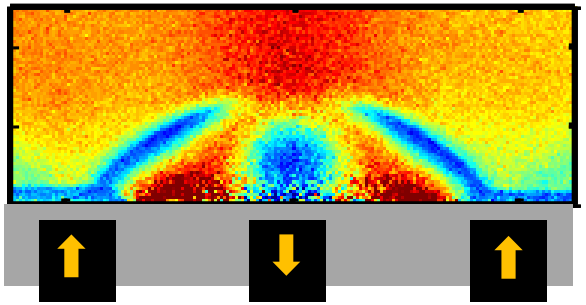
Challenges in Plasma Diagnostics

- The most relevant and interesting physics happens in relatively small regions of the plasma, as the plasma is non-uniform and dynamic.
- Therefore, plasma diagnostic tools need to have sufficient spatial and temporal resolution.
- Develop and apply improved non-intrusive plasma diagnostics, with resolution high enough to address spatial and temporal changes of the critical plasma parameters.

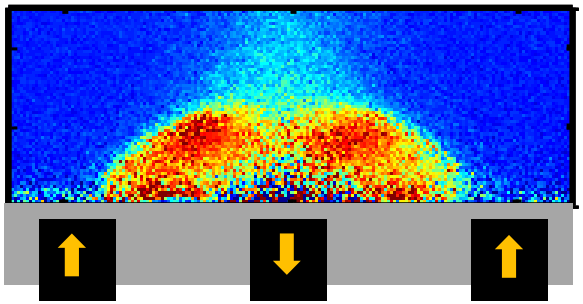
$1s_5$ Distribution
[418 nm LIF]



Electron density
$2x10^{11}$ e/cm^3 full scale
[675 nm LCIF]/[418 nm LIF]



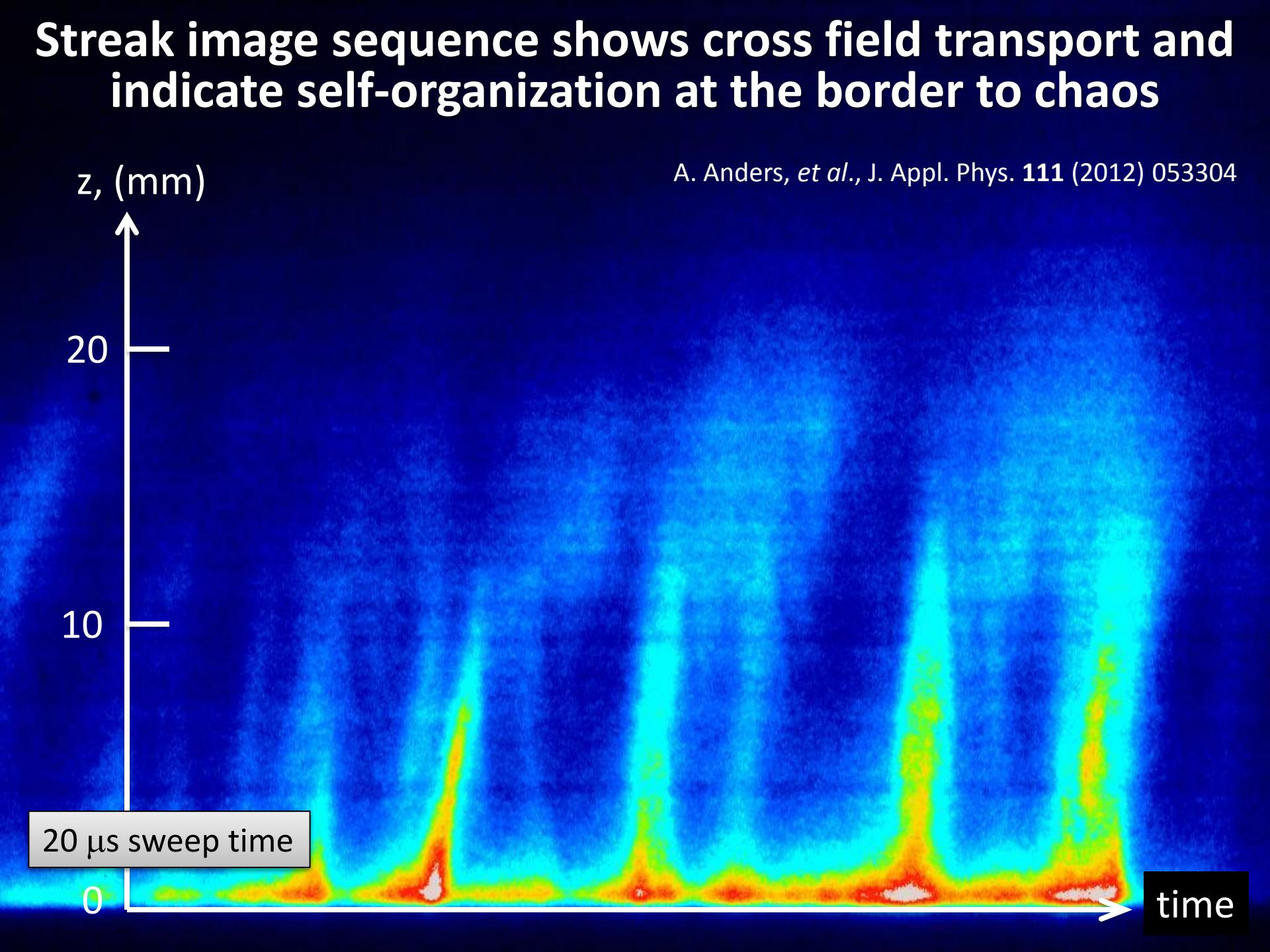
E/N
[590 nm LCIF]/[675 nm LIF]
30 Td full scale



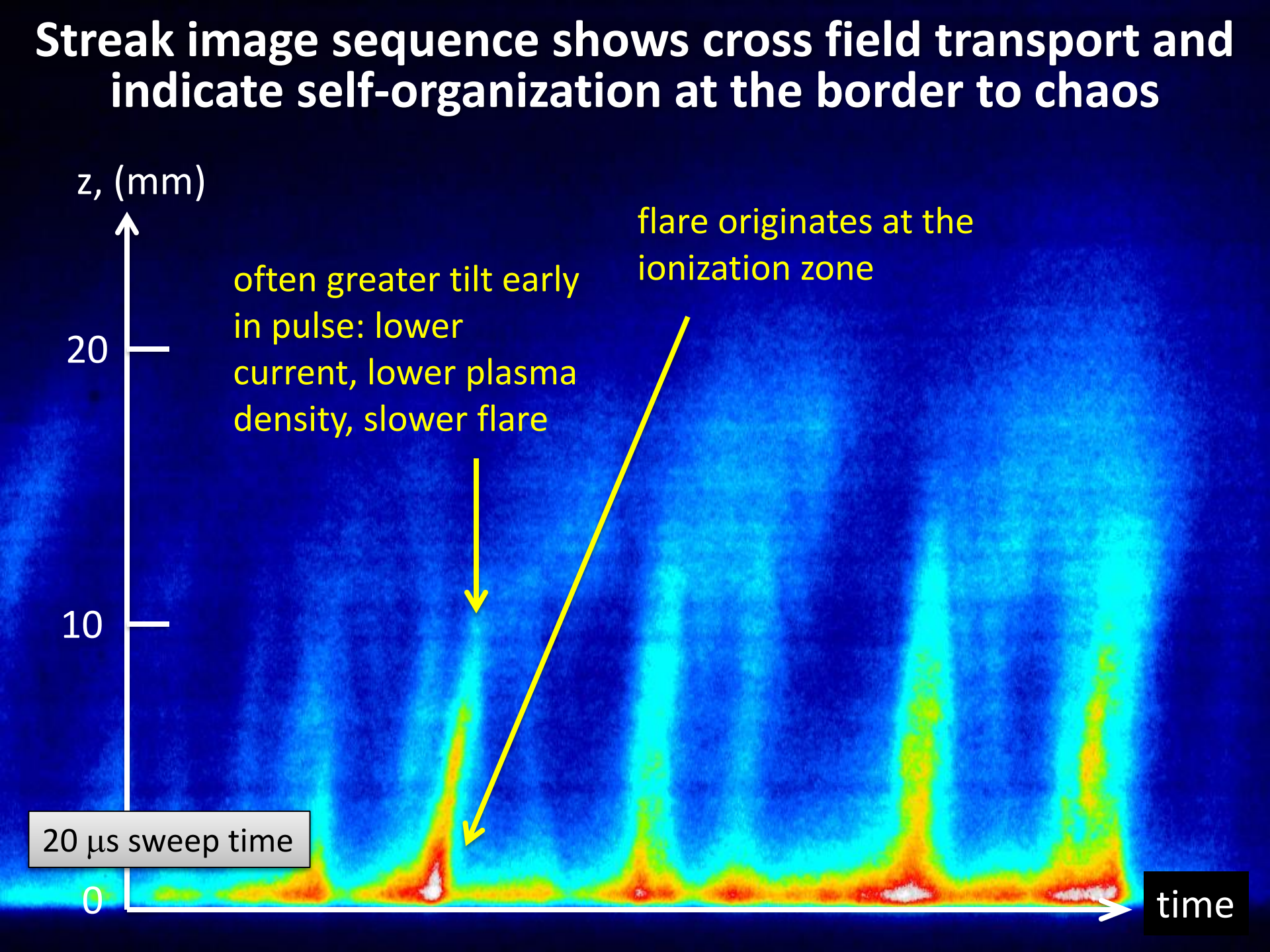
E.V. Barnat, B.R. Weatherford, Plasma Sources Sci. Technol. (2015) submitted for review.

Streak image sequence shows cross field transport and indicate self-organization at the border to chaos

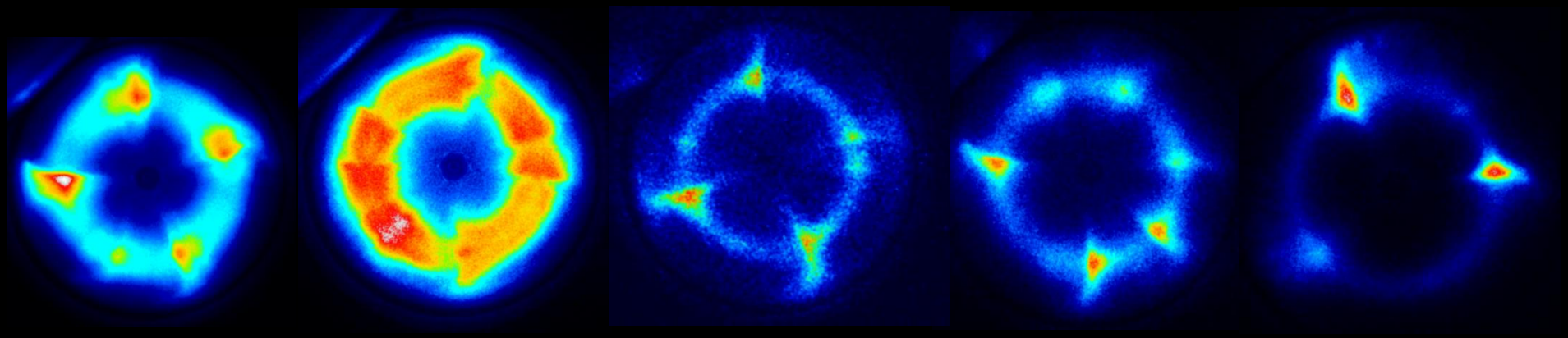
A. Anders, *et al.*, J. Appl. Phys. **111** (2012) 053304



Streak image sequence shows cross field transport and indicate self-organization at the border to chaos



Spectroscopically Resolved, Fast Imaging



300-800 nm | Al I, from 3.14 eV | Ar I from 13.3 eV | Al II, from 15.06 eV | Ar II, from 19.22 eV

Al, 0.25 Pa Ar, 100 A, 150 ns snapshots

→ the higher the upper excitation level the more focussed appears the plasma,

→ evidence of structure, self-organized electron heating

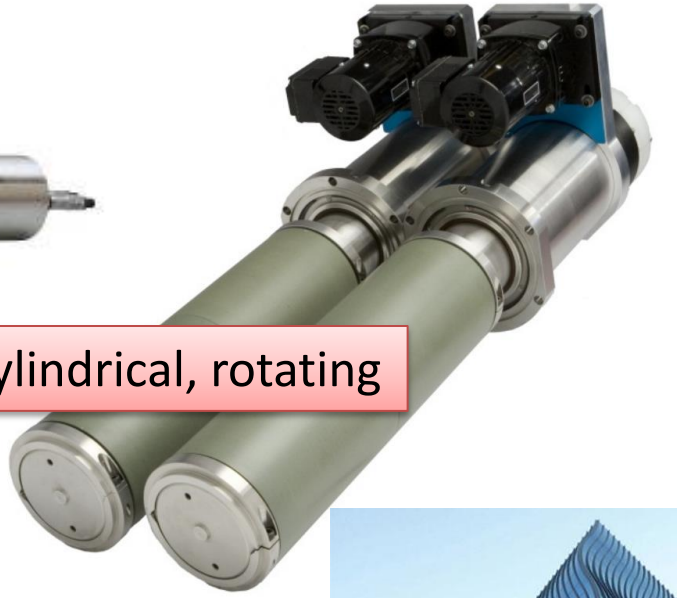
A. Andersson, *et al.*, Appl. Phys. Lett. **103** (2013) 054104.

Why do we care? Implications.

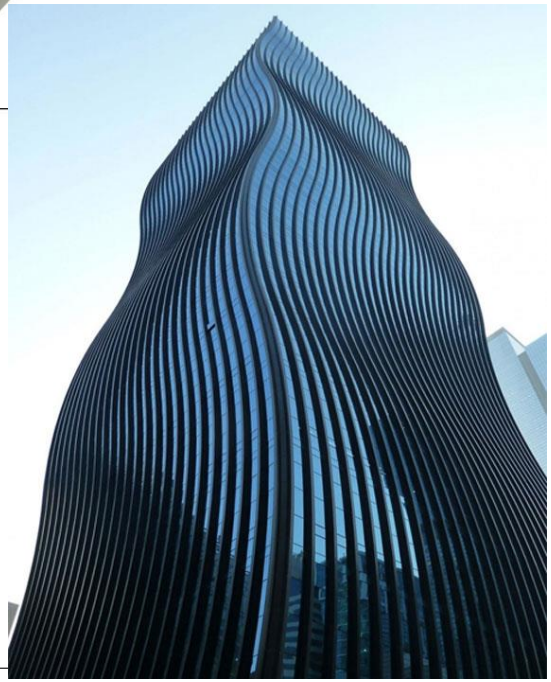
Example: magnetrons

dual, planar, rectangular

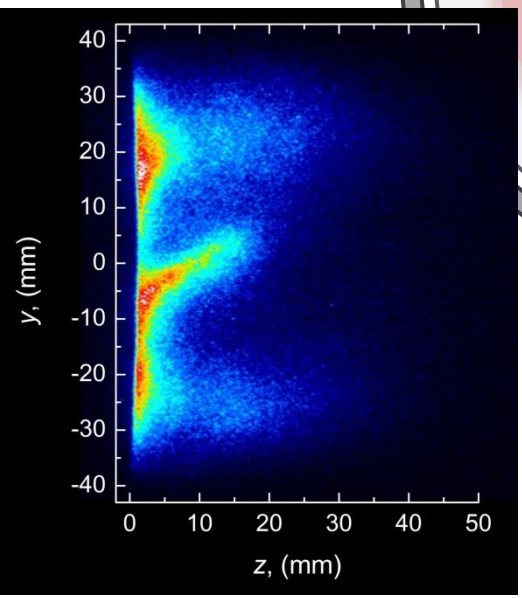
planar, round

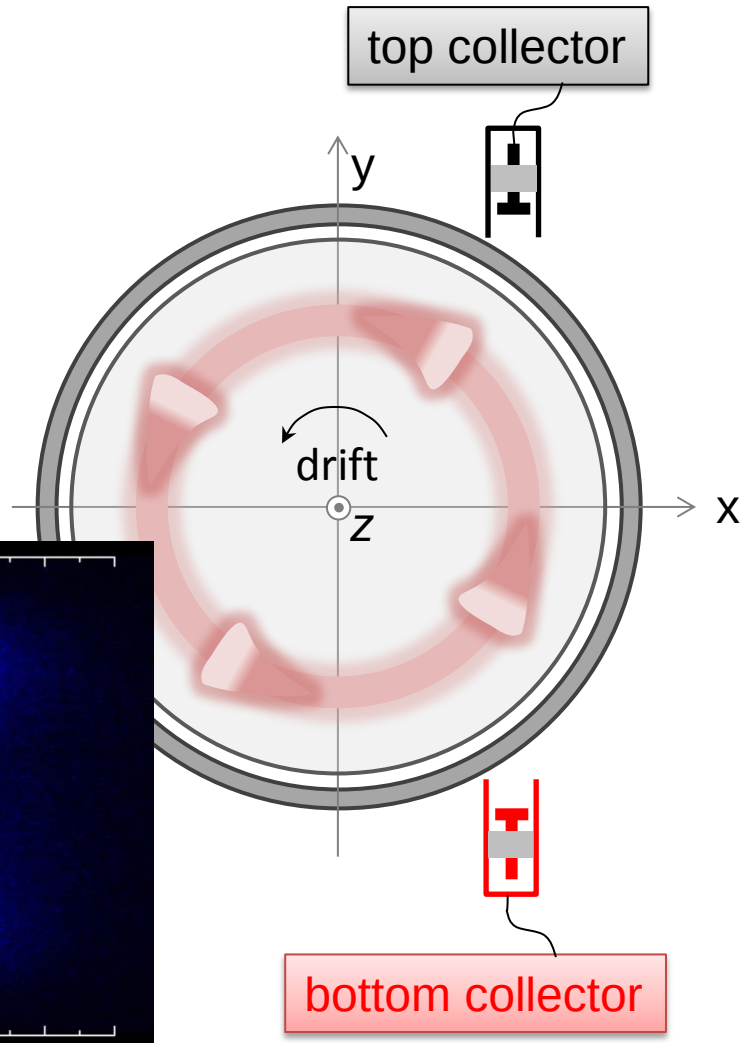


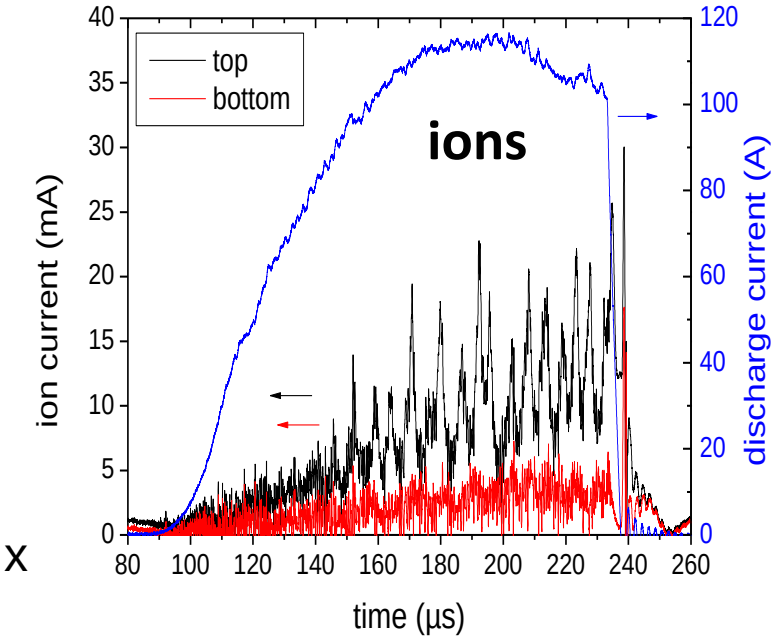
dual, cylindrical, rotating

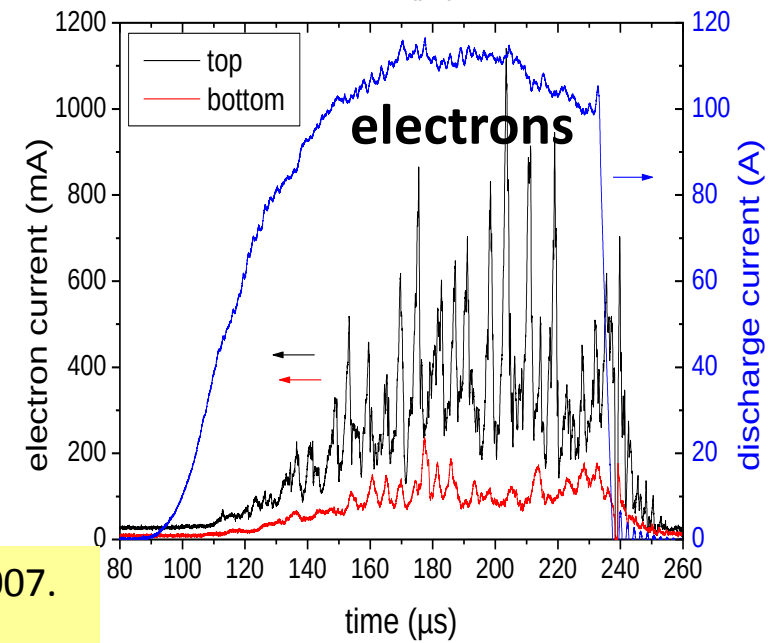


Ionization zones and cross-field transport of charged particles





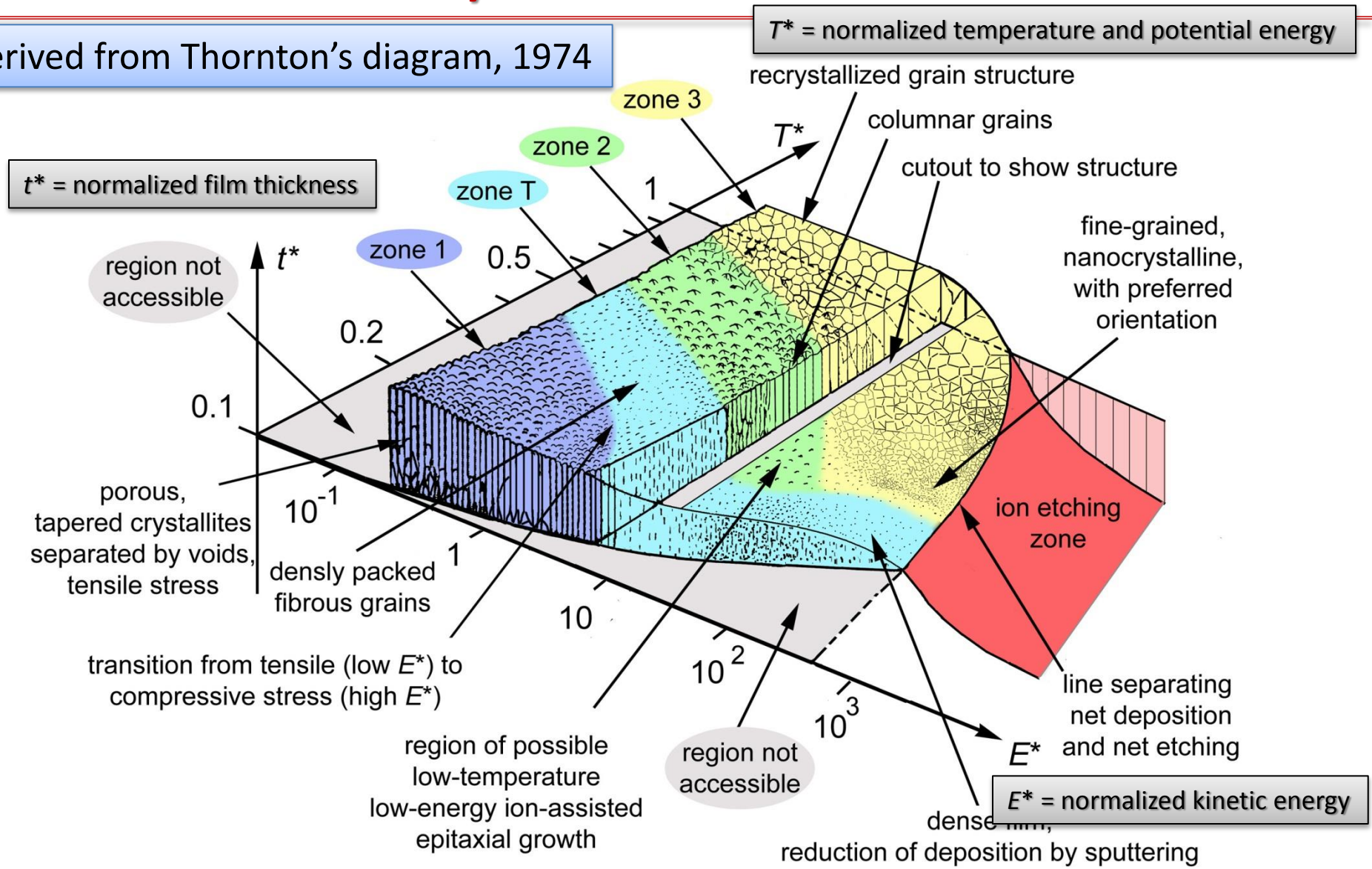




M. Panjan, *et al.*, *Plasma Sources Sci. Technol.*, **23** (2014) 025007.
A. Anders, *et al.*, J. Appl. Phys. **111** (2012) 053304

A Generalized Structure Zone Diagram for Film Microstructure Obtained by Plasma-Assisted Film Growth

derived from Thornton's diagram, 1974



A. Anders, Thin Solid Films **518** (2010) 4087

Big Questions: The Frontiers

1. Is there a **common underlying physics** for self-organization in ExB discharges? If yes, what is this?

   Note: Different low-temperature plasma system suggest that. However, processes are different than with fusion plasmas as ions are not magnetized.

2. Can we **model self-organization** for ExB discharges, and low-temperature plasmas in general, for a wide range of conditions, and validate the models?

3. Can self-organization be **controlled** with the goal to either *utilize* or *suppress* it for the benefit of the application?

4. Can we gain new insights by *simultaneously* resolving plasma properties: the "**Resolution Frontier**".

Low-temperature Plasma Physics Program & Facilities

There should be
a coordinated US program for low-temperature plasma physics.

- Current low-temperature plasma facilities in the US are small and scattered at different universities and labs. *Note: Larger European funding programs have enhanced Europe's competitiveness.*
- A Program, coordinated by DOE, DOD, NSF, NASA, supporting ***multiple facilities*** can address fundamental questions as well as those relevant to industry .
- Each of such facility has relatively modest needs by the standards of other plasma facilities.
- Make use of DOE user facilities, incl. ***high performance computing*** centers and light sources.
- Need for ***advanced experimental systems*** that have the capability of *simultaneously* resolving plasma properties in time, space, charge state, energy distributions.