Numerical Modeling of Plasma Striations

2021 Princeton Plasma Physics Laboratory
Graduate Summer School

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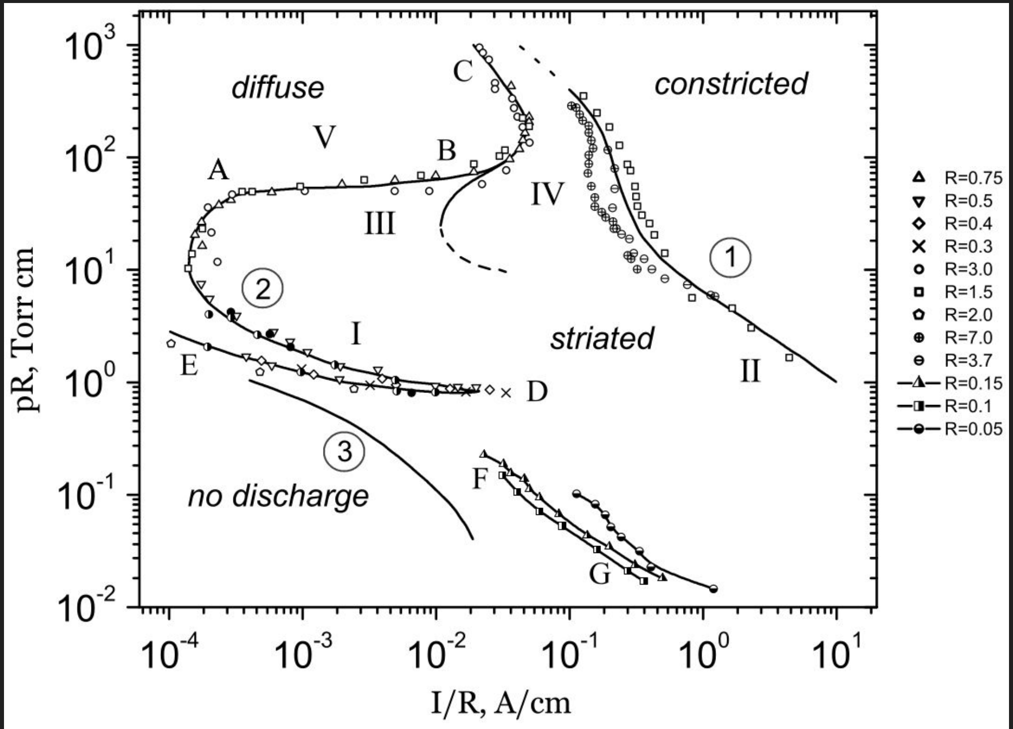
What are plasma striations and why do we care?

- Formation of spatial patterns along the discharge current
  - light emission, ne, Te, etc
- Multiple proposed mechanisms
  - e.g. non-linear dependence of ionization rate on electron density
- Observed experimentally for a long time but still not fully understood

V. I. Kolobov et al, 2020 J. Phys. D: Appl. Phys. 53 25LT01 (5pp)

Courtesy of Dr Ed Thomas, Auburn University

Current state of the field (1)



V. I. Kolobov, 2006 J. Phys. D: Appl. Phys. 39 R487-R506

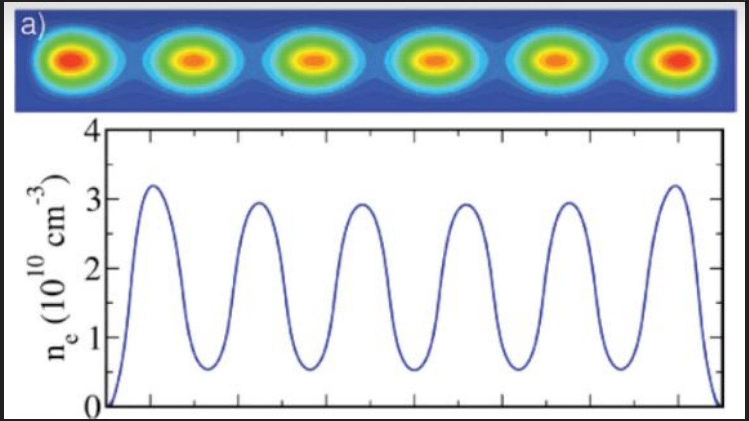
- Structures vary widely with experimental setup
  - discharge current (I)
  - gas pressure (p)
  - tube radius (R)
  - chemical composition
  - circuitry: DC, CCP, ICP, RF

- Scaling laws
  - plasmas with similar "combination" of parameters exhibit similar behavior

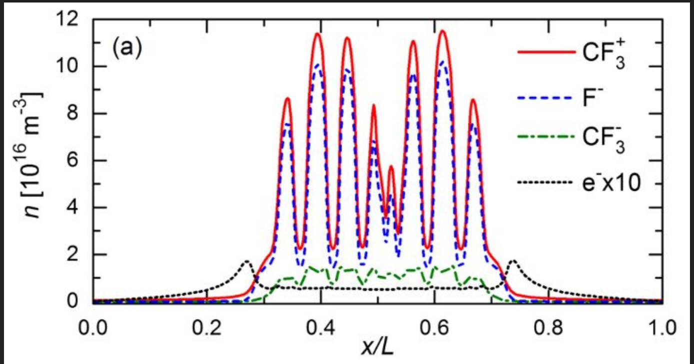
Current state of the field (2)

- Fluid simulations of striations along Pupp boundary obtained only recently

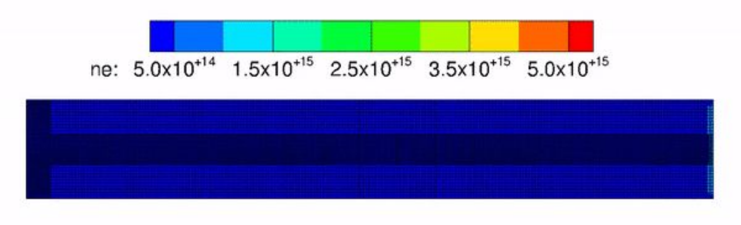
- PIC simulations have produced striations for lower current setups



V. I. Kolobov et al., 2020 J. Phys. D: Appl. Phys. 53 25LT01



Y.-X. Liu et al., 2016 Phys. Rev. Lett. 116 055024



R. R. Arslanbekov and V. I. Kolobov, 2021 Plasma Sources Sci. Technol. 30 045013

Our research

Non-local kinetic description for electrons

$$f(\mathbf{x}, \mathbf{v}, t) = f_0(\mathbf{x}, v, t) + \mathbf{v} \bullet \mathbf{f}_1(\mathbf{x}, v, t)/v,$$

$$v \frac{\partial f_0}{\partial t} + \nabla \bullet \mathbf{\Phi} + \frac{\partial \Gamma_u}{\partial u} = v\, C_0^{inelastic},$$

$$\mathbf{\Phi} = \frac{v^2 \mathbf{f}_1}{3} = -v D_r \left(\nabla f_0 - \frac{e\mathbf{E}}{w_0} \frac{\partial f_0}{\partial u} \right),$$

$$\Gamma_u = -\frac{e}{w_0} \mathbf{E} \bullet \mathbf{\Phi} - (D_{elastic} + D_{ee}) \frac{\partial f_0}{\partial u} - (V_{elastic} + V_{ee}) f_0.$$

Fluid description for ions

$$\frac{\partial n_+}{\partial t} + \nabla \bullet \mathbf{\Gamma}_+ = S_+,$$

$$\mathbf{\Gamma}_+ = -D_+ \nabla \bullet n_+ + \mu_+ \mathbf{E}\, n_+,$$

Poisson eq. for electric field

$$\nabla \cdot (\nabla \varphi) = -\frac{e}{\varepsilon_0} (n_+ - n_e),$$

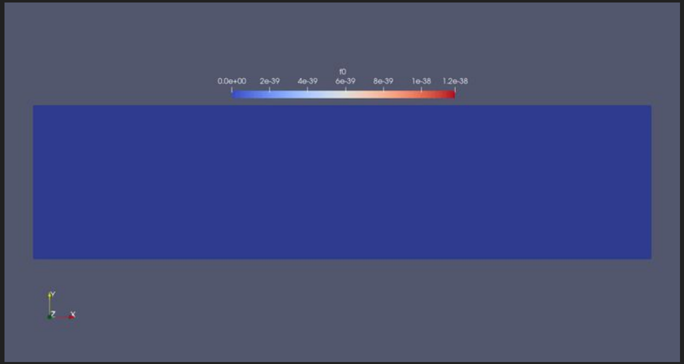
$$\mathbf{E} = -\nabla \varphi.$$

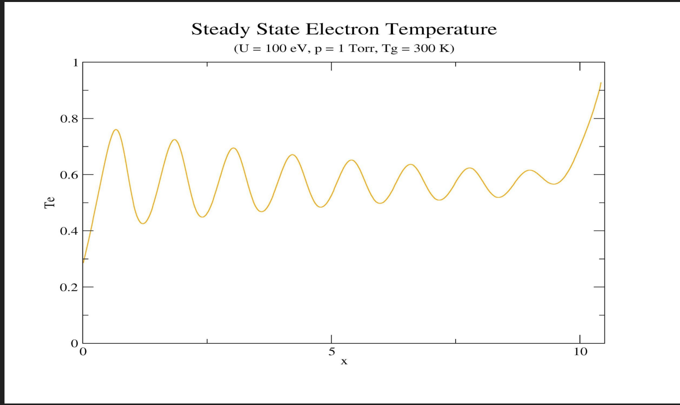
C. Yuan, et al., 1D kinetic simulations of a short glow discharge in helium, PHYSICS OF PLASMAS 24, 073507 (2017)

- Solving system while comparing capabilities of different softwares (COMSOL & Basilisk C)

Basilisk C

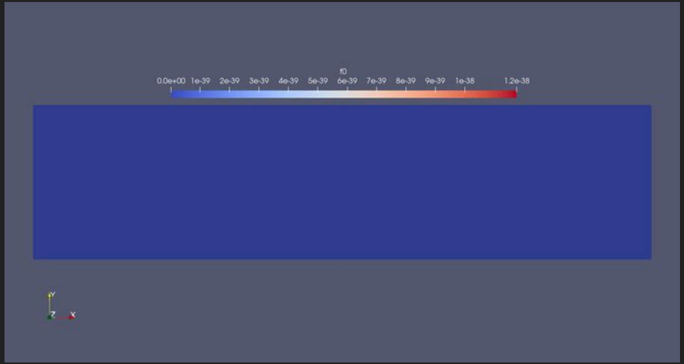
- Finite Volume method
- Explicit and implicit time treatment developed
- Use of limiters in explicit code in order to maintain $f_0 > 0$
- Boundary conditions are non-trivial to implement due to full tensor diffusion

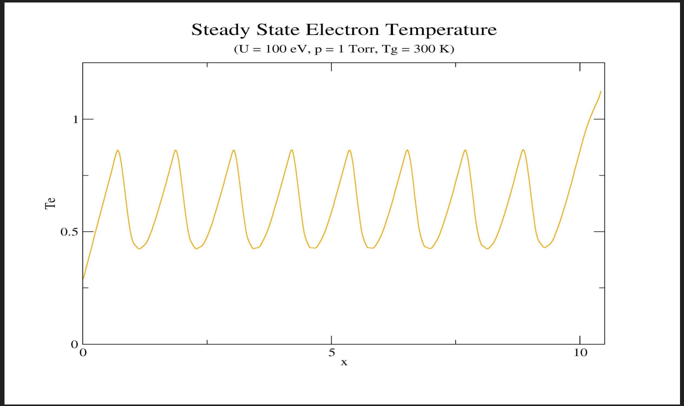




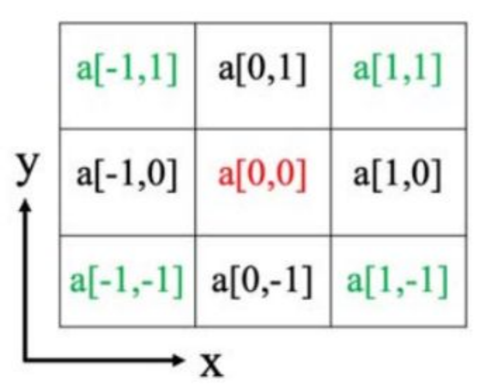
Slope limiters

- Used to prevent unphysical negative values of f_0 due to tangential fluxes
- Most limiters add numerical damping to the spatial profiles
- Superbee limiter (anti-diffusive) removes damping





Time step coupling method (in Basilisk)



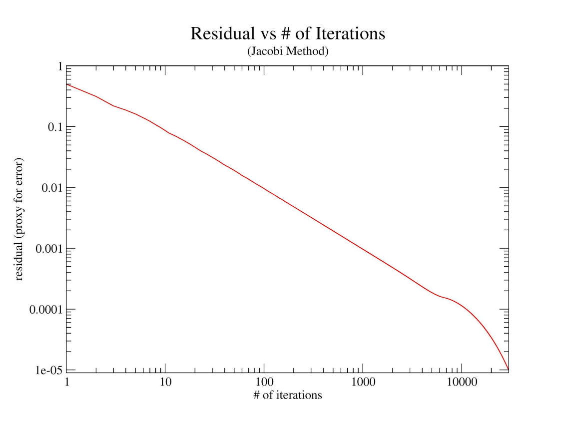
1. Start with f_0, n_i and φ at time t
2. Find f_0 at time t + Δt using n_i and φ at time t (*)
3. Find n_i at time t + Δt using f_0 and φ at time t (**)
4. Find φ at time t + Δt using updated f_0 and n_i (**)
5. Repeat from step (1.)

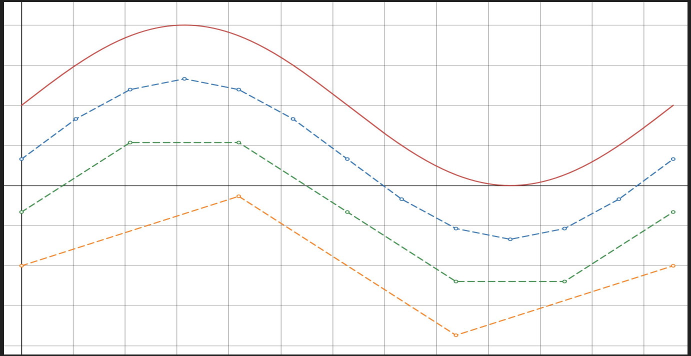
(*) Diffusion-Reaction eq. $\xrightarrow{\Delta t}$ Poisson-Helmholtz eq. (solved with multigrid method)

(**) Tridiagonal system for 1D1E system

Multigrid method

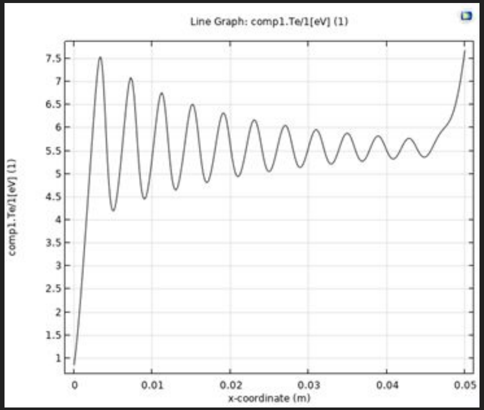
- Method of successive relaxations:
  - Discretized PDE = Linear system with one equation per cell/grid point
  - Solve recursively via Jacobi or Gauss-Seidel iterations
- Multigrid “enhancement”:
  - “Diminishing returns” in error reduction due to smooth errors persisting
  - Faster convergence by cycling through coarser and finer grids

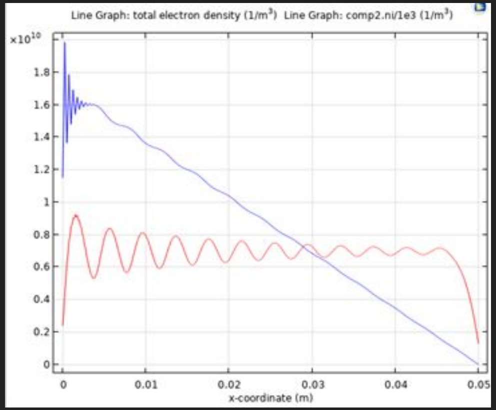


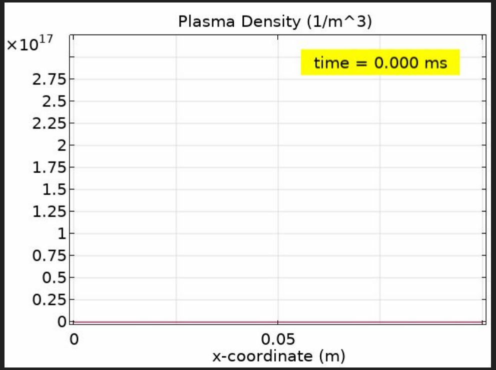


COMSOL

- Finite Element method
- Multiple options available for time stepping
- Natural log formalism in order to maintain $f_0 > 0$
- Some features are “hidden” and not easily accessible, so it’s a bit of a “black box” at times







Useful references

- Two-term spherical harmonic expansion: U. Kortshagen, C. Busch and L. D. Tsendin, On simplifying approaches to the solution of the Boltzmann equation in spatially inhomogeneous plasmas, PLASMA SOURCES SCIENCE AND TECHNOLOGY 5, 1 (1996)
- Multigrid method: W. L. Briggs, V. E. Henson, and S. F. McCormick A multigrid tutorial, 2nd edition (Jan 2000)
- Use of slope limiters in tensor diffusion: P. Sharma, G. W. Hammett, Preserving monotonicity in anisotropic diffusion, JOURNAL OF COMPUTATIONAL PHYSICS 227, 123-142 (2007)

Thank you for your attention

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