RUHR-UNIVERSITÄT BOCHUM

3D PIC magnetron simulations on GPU

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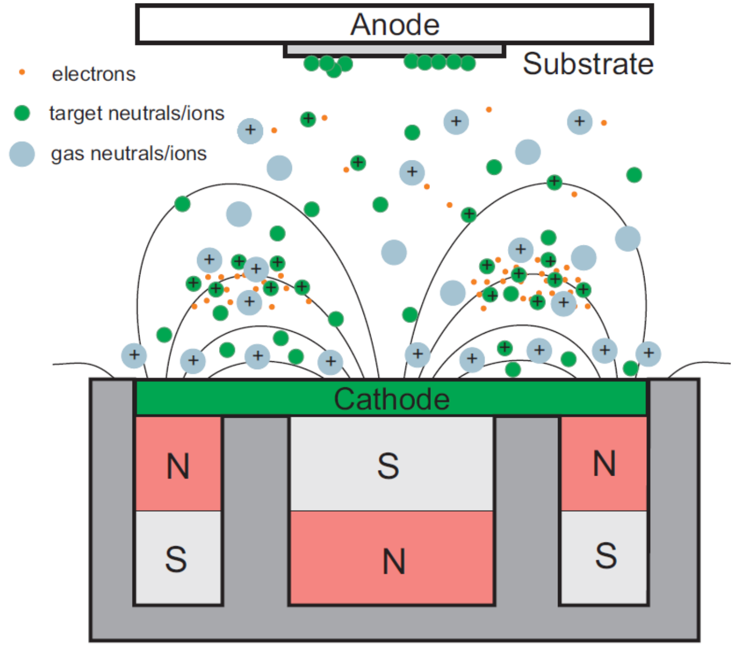
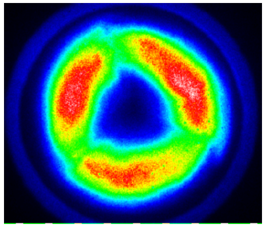
THEORETISCHE TET ELEKTROTECHNIK

SFB-TR 87

Motivation



spokes



anomalous
transport

Challenge:

3D effects might be important due to excitation of additional modes and changes in behavior of the ECDI

Explicit PIC Limitations

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Spatial grid size:

- $\Delta x \leq \lambda_{De}$ (numerical heating)

  this results in approx. 5000 x 5000 2D grids
  for discharges with electron density 1.e19 per cubic meter
  and (R,d) = 5 cm

Time step:

- $\Delta t \leq \omega_{pe}^{-1}$ (numerical heating)
- CFL condition (numerical stability, accuracy)
- $\Delta t \leq \nu_{eff}^{-1}$ accuracy
- $\Delta t \leq \omega_{Be}^{-1}$ accuracy

Implicit ECPIC algorithm (Eremin)   Gyrokinetic approach (Brinkmann, Krüger)

Energy conserving PIC algorithm

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[Chen et al, JCP 2011], [Markidis et al, JCP, 2011]

Crank-Nicolson orbit integrator

$$\frac{\mathbf{v_j}^{\mathbf{n+1}} - \mathbf{v_j^n}}{\Delta t} = \frac{q}{2m} \sum_{\alpha} \left(\mathbf{E}_{\alpha}^{\mathbf{n+1}} + \mathbf{E}_{\alpha}^{\mathbf{n}}\right) S(\mathbf{x}_{\alpha} - \mathbf{x}_{\mathbf{j}}^{\mathbf{n+1/2}})$$

$$\frac{\mathbf{x}_{\mathbf{j}}^{\mathbf{n+1}} - \mathbf{x}_{\mathbf{j}}^{\mathbf{n}}}{\Delta t} = \frac{\mathbf{v}_{\mathbf{j}}^{\mathbf{n+1}} + \mathbf{v}_{\mathbf{j}}^{\mathbf{n}}}{\mathbf{2}}$$

Field equation

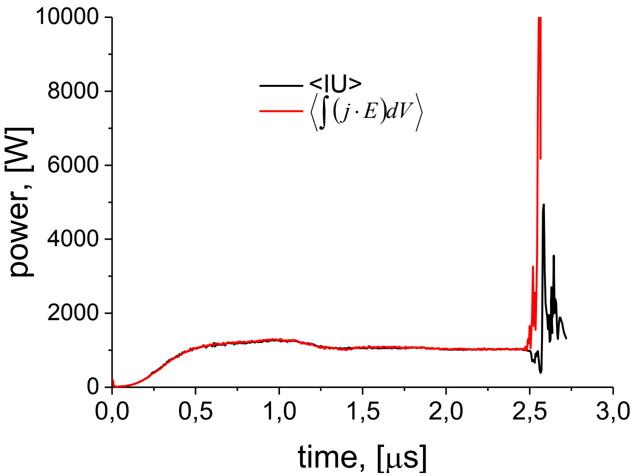
$$\nabla \cdot \left(\mathbf{j}^{\mathbf{n+1/2}} + \epsilon_0 \frac{\mathbf{E}^{\mathbf{n+1}} - \mathbf{E}^{\mathbf{n}}}{\Delta t}\right) = 0$$

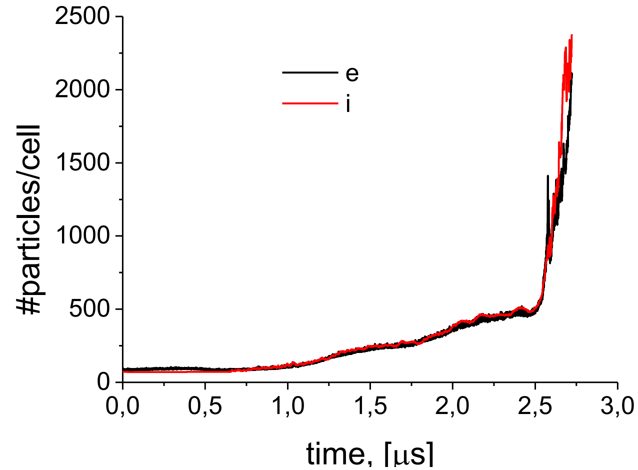
$$\mathbf{j}_{\alpha}^{\mathbf{n}} = \frac{q}{2\Delta V_{\alpha}} \sum_{j} \mathbf{v}_{\mathbf{j}}^{\mathbf{n+1/2}} S(\mathbf{x}_{\alpha} - \mathbf{x}_{\mathbf{j}}^{\mathbf{n+1/2}})$$

iterate to tight convergence

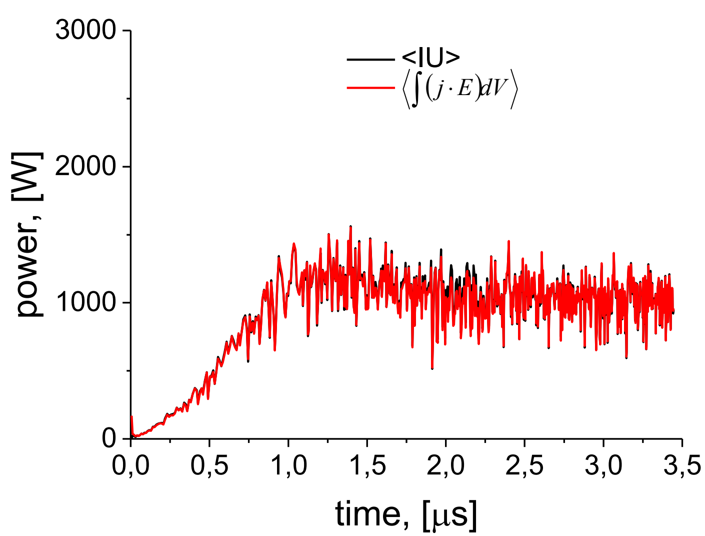
Adaptive Time Step

Energy is conserved as long as the iterations converge. What if they don't?





Remedy: adaptive timestep with controlled iteration convergence



3D PIC in cylindrical coordinates

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3D PIC ES code for HPPMS Simulations:

Fourier decomposition in the azimuthal direction,

$$\phi(r,\theta,z) = \frac{\phi^0(r,z)}{2} + \sum_{1\leq n\leq N_{max}} [\phi_c^n(r,z)\cos(2\pi n\theta) + \phi_s^n(r,z)\sin(2\pi n\theta)]$$

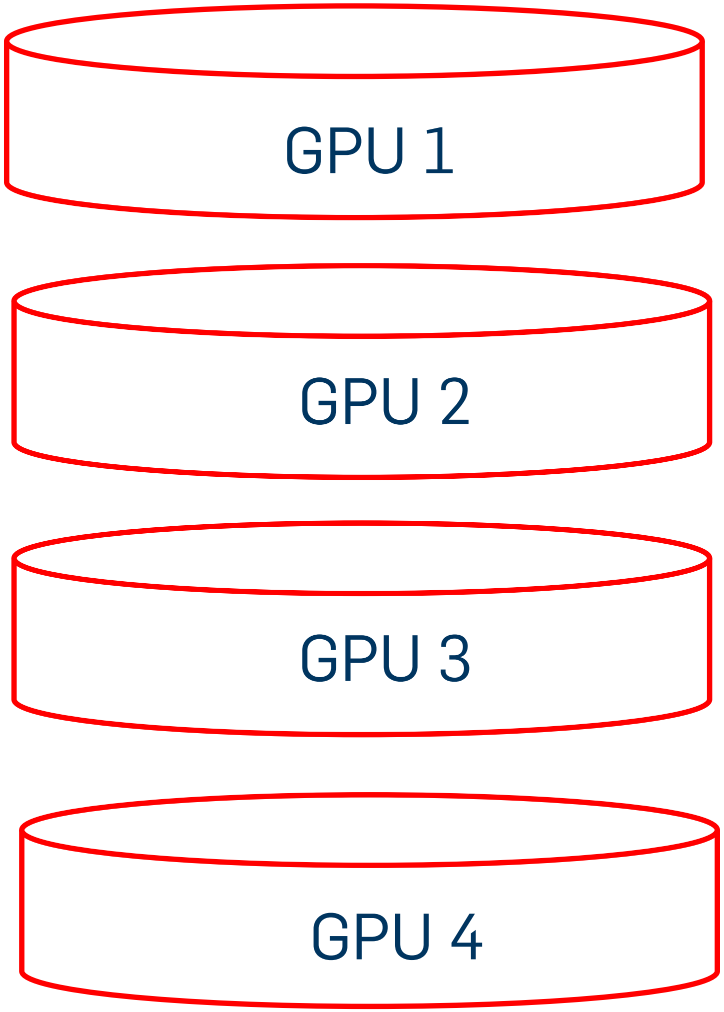
Elliptic equations for the potential harmonics

$$\frac{1}{r}\frac{\partial}{\partial r}\frac{\partial}{\partial r}\phi^n - \frac{n^2}{r^2}\phi^n + \frac{\partial^2}{\partial z^2}\phi^n = S^n$$

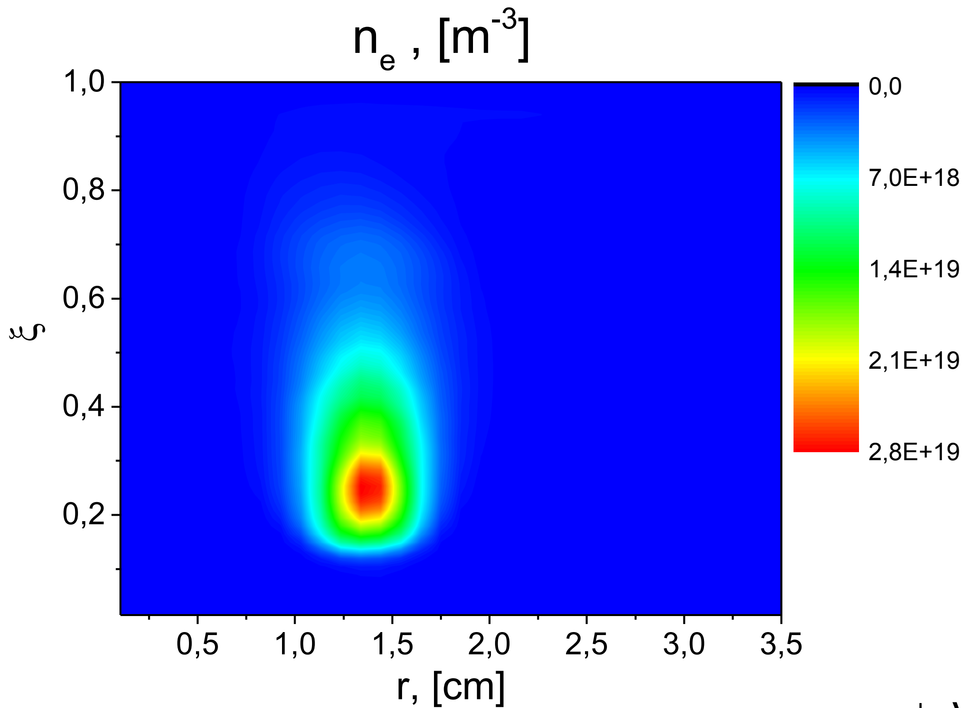
can be solved for each harmonics in parallel

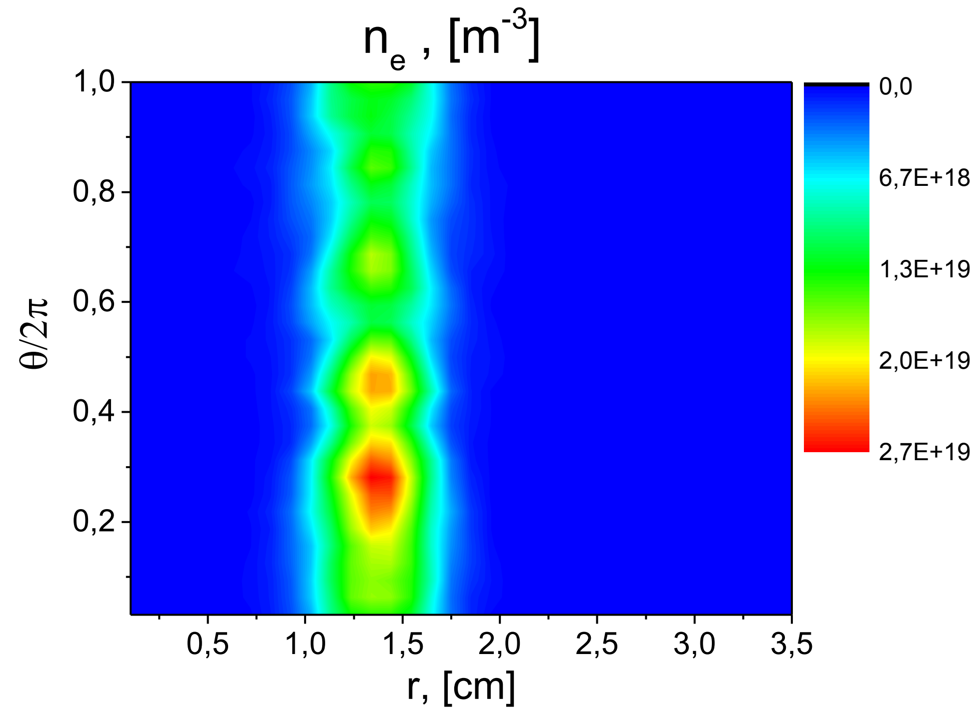
$$E^n_{r,\{c,s\}} = -\frac{\partial}{\partial r}\phi^n_{\{c,s\}} \qquad E^n_{r,\{c,s\}} = \mp 2\pi n\phi^n_{\{s,c\}} \qquad E^n_{z,\{c,s\}} = -\frac{\partial}{\partial z}\phi^n_{\{c,s\}}$$

Multi-GPU implementation

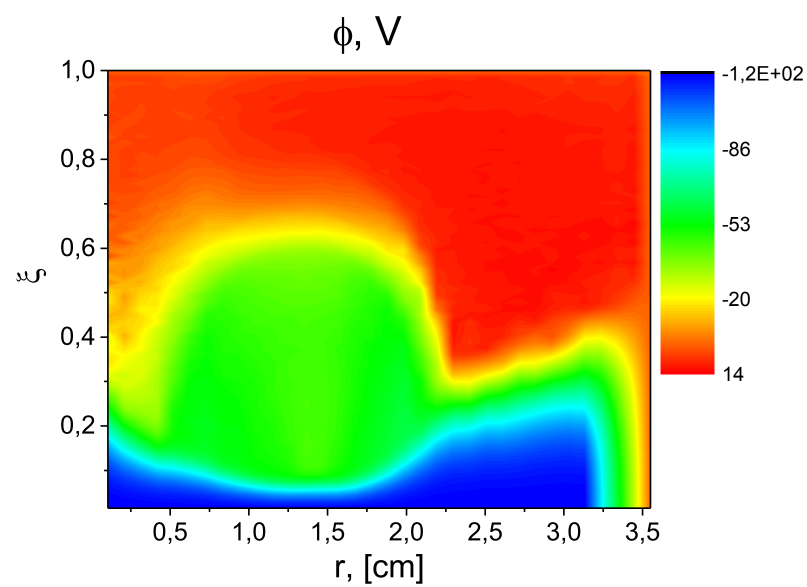


Some results





sheath/bulk power for electrons = 27 %



Acknowledgments

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