Unintended gas breakdowns in narrow gaps of advanced plasma sources for semiconductor fabrication industry

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Talk Overview

1. Context and motivation
2. Kinetic modeling via Particle-In-Cell simulation using EDIPIC-2D
3. Results and discussion
4. Modeling capabilities and expertise at PPPL via PCRF

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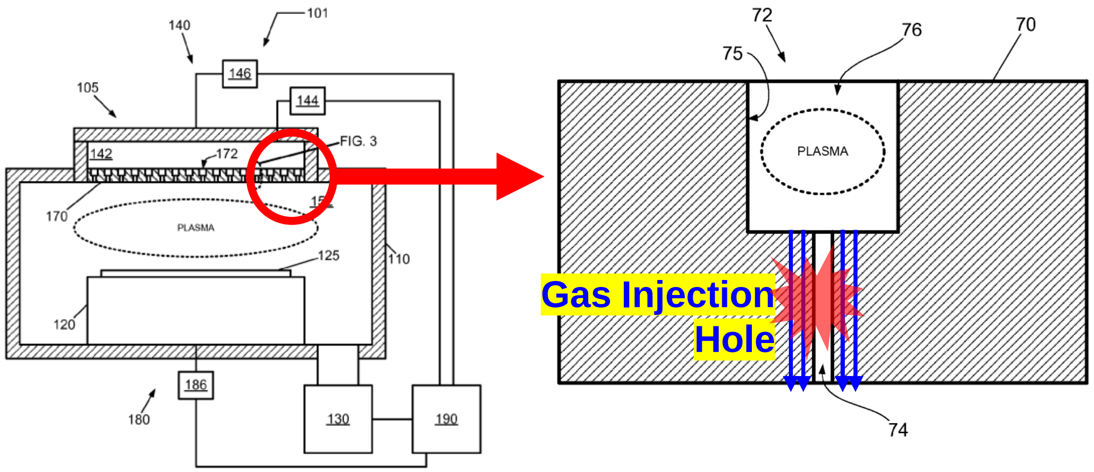
Context and Motivation

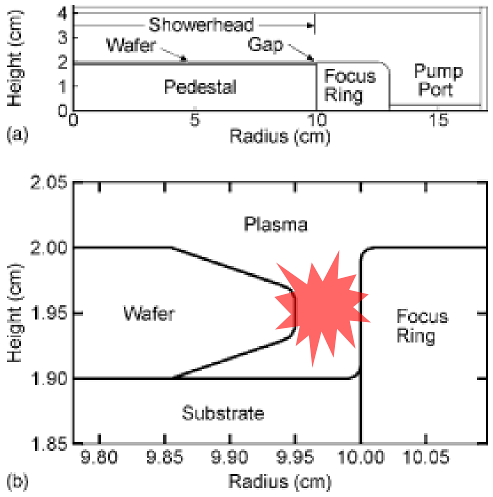


Processing chamber for ICP/CCP (left) and corresponding injection hole (right) [1]

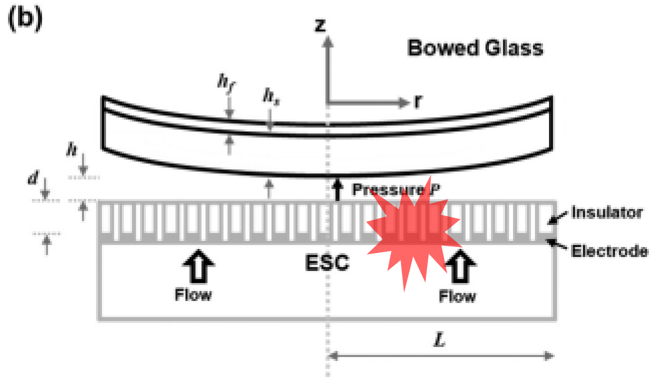
Consequences?

Chamber lifetime, Reliability ↓

Similar **narrow gap structures in various sources**, also could be vulnerable



Gap between focus ring and wafer (CCPs) [2]



Wafer backside cooling channel (CCPs/ICPs)[3]

[1] Chen Lee, and Lin Xu., U.S. Patent No. 7,744,720 (2010)

[2] N.Y. Babaeva, and M.J. Kushner, Journal of Applied Physics **101**(11), 113307 (2007)

[3]S. Park, *et al.*, Physics of Plasmas **28**(10), 103505 (2021)

Context and Motivation

Classical Paschen law

$$V_b = \frac{Bpd}{\left[\ln\left(Apd\right) - \ln\left\{\ln\left(1+1/\gamma_{SE}\right)\right\}\right]}$$

A,B : Gas dependent constants

γ_{SE} : Ion induced SEE coefficient

→ Assumes 1D Townsend discharge

(Which is very simple)

More complex configuration

Modified Paschen law[1]

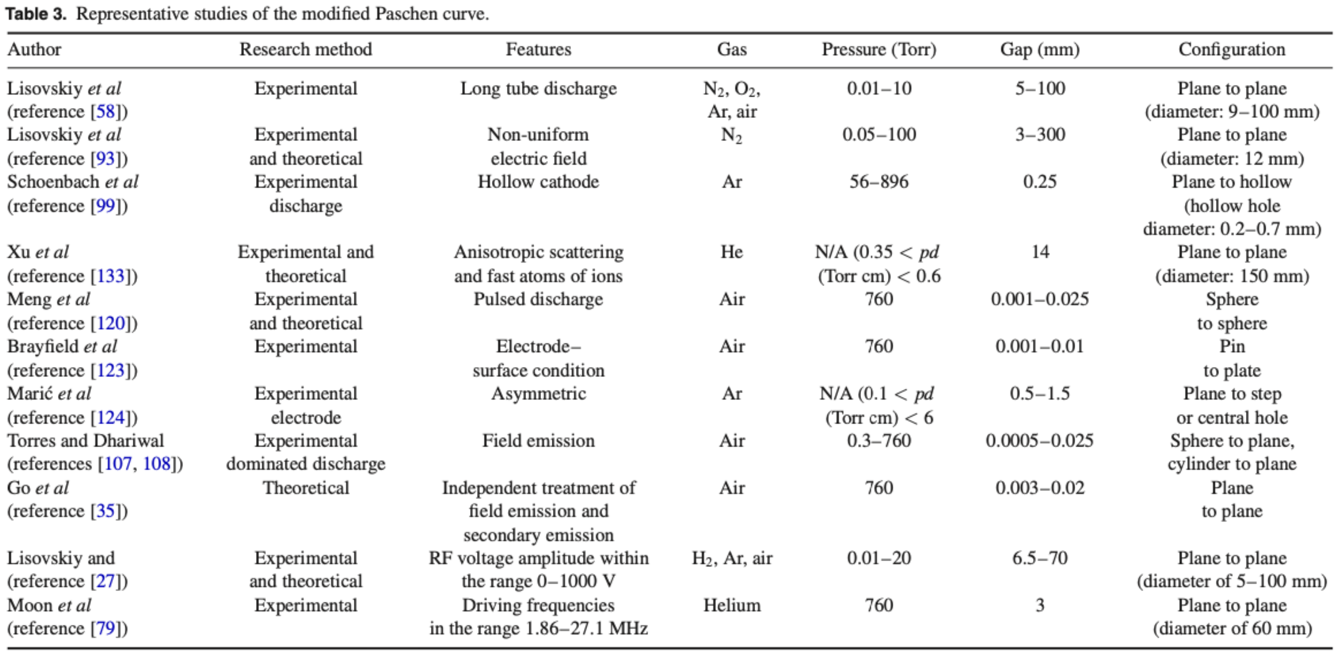


Table 3. Representative studies of the modified Paschen curve.

Author	Research method	Features	Gas	Pressure (Torr)	Gap (mm)	Configuration
Lisovskiy *et al* (reference [58])	Experimental	Long tube discharge	N_2, O_2, Ar, air	0.01–10	5–100	Plane to plane (diameter: 9–100 mm)
Lisovskiy *et al* (reference [93])	Experimental and theoretical	Non-uniform electric field	N_2	0.05–100	3–300	Plane to plane (diameter: 12 mm)
Schoenbach *et al* (reference [99])	Experimental discharge	Hollow cathode	Ar	56–896	0.25	Plane to hollow (hollow hole diameter: 0.2–0.7 mm)
Xu *et al* (reference [133])	Experimental and theoretical	Anisotropic scattering and fast atoms of ions	He	N/A (0.35 < *pd* (Torr cm) < 0.6	14	Plane to plane (diameter: 150 mm)
Meng *et al* (reference [120])	Experimental and theoretical	Pulsed discharge	Air	760	0.001–0.025	Sphere to sphere
Brayfield *et al* (reference [123])	Experimental	Electrode–surface condition	Air	760	0.001–0.01	Pin to plate
Marić *et al* (reference [124])	Experimental electrode	Asymmetric	Ar	N/A (0.1 < *pd* (Torr cm) < 6	0.5–1.5	Plane to step or central hole
Torres and Dhariwal (references [107, 108])	Experimental dominated discharge	Field emission	Air	0.3–760	0.0005–0.025	Sphere to plane, cylinder to plane
Go *et al* (reference [35])	Theoretical	Independent treatment of field emission and secondary emission	Air	760	0.003–0.02	Plane to plane
Lisovskiy and (reference [27])	Experimental and theoretical	RF voltage amplitude within the range 0–1000 V	H_2, Ar, air	0.01–20	6.5–70	Plane to plane (diameter of 5–100 mm)
Moon *et al* (reference [79])	Experimental	Driving frequencies in the range 1.86–27.1 MHz	Helium	760	3	Plane to plane (diameter of 60 mm)

Narrow gap breakdown even more complex;
e.g., presence of background plasma

We conduct experiments and simulations to investigate the breakdown

[1] J.Y. Kim, *et al.* Plasma Sources Sci. Technol. **31**(3), 033001 (2022)

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Our PIC code EDIPIC 2D

Use of EDIPIC-2D code, based on earlier 1D version [1]

- ✓ Comprehensive 2D Cylindrical/Cartesian explicit PIC code.
- ✓ State-of-the art collision models. FFT methods or PETSc library for Poisson solver. External circuits. Inner objects
- ✓ Verified in international benchmarks [1,2,3,4]
- ✓ Numerous users from academia and industry

More info at poster session!

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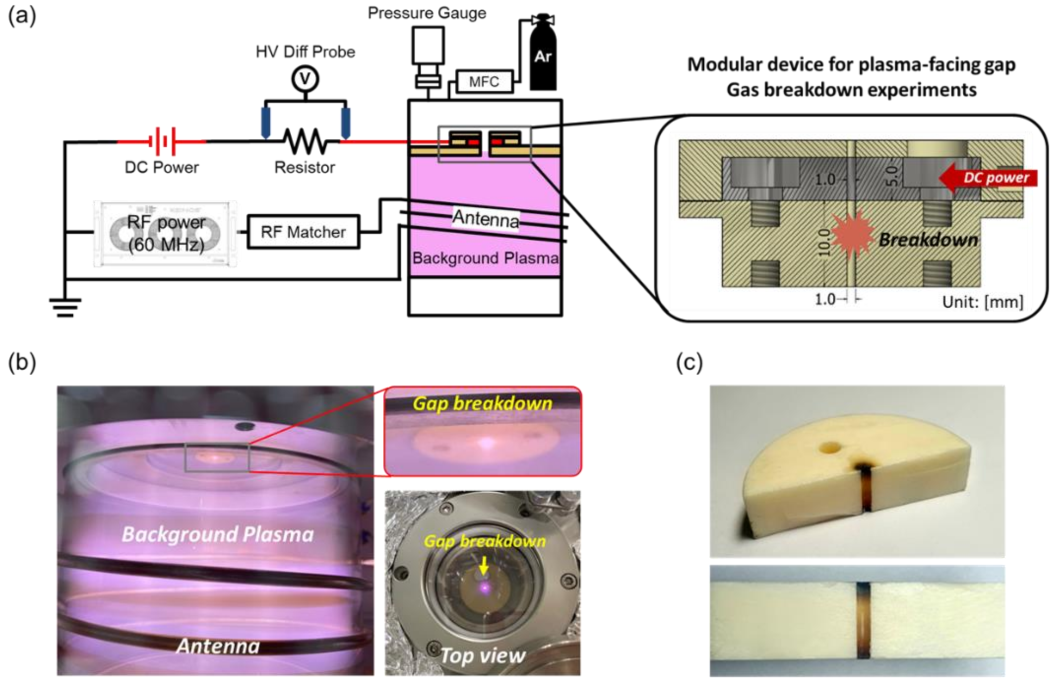
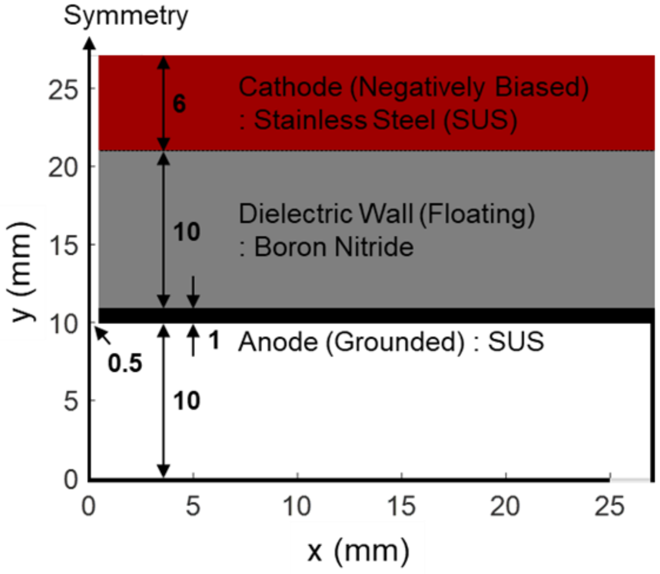
Open source and portable code able to simulate a wide variety of low temperature plasma physics problems
https://github.com/PrincetonUniversity/EDIPIC-2D

[1] Sydorenko, PhD thesis, (2006)
[2] T. Charoy, *et al.*, Plasma Sources Sci. Technol. 28(10), 105010 (2019).
[3] W. Villafana *et al.*, Physics of Plasmas **30**(3), 033503 (2023)
[4] M.M. Turner *et al.*, Physics of Plasmas 20(1), 013507 (2013).

Configuration and numerical setup [1]



Experimental setup performed at SNU. (a) ICP schematic. (b) Breakdown during operation (c) inner surface after several discharges.



Numerical setup with EDIPIC

- ✓ Electron-induced Secondary Electron Emission is based on Vaughan's model [2]
- ✓ Ion-induced Secondary Electron Emission
- ✓ Initial conditions: Uniform Argon plasma, density n_0, Maxwellian distribution, temperatures $T_{e,0}$ & $T_{i,0}$
- ✓ Bias cathode voltage V_{cat}

[1]S.H. Son, *et al.* Applied Physics Letters **123**(23), 232108 (2023)

[2]J.R.M. Vaughan, IEEE Trans. Electron Devices **36**(9), 1963–1967 (1989)

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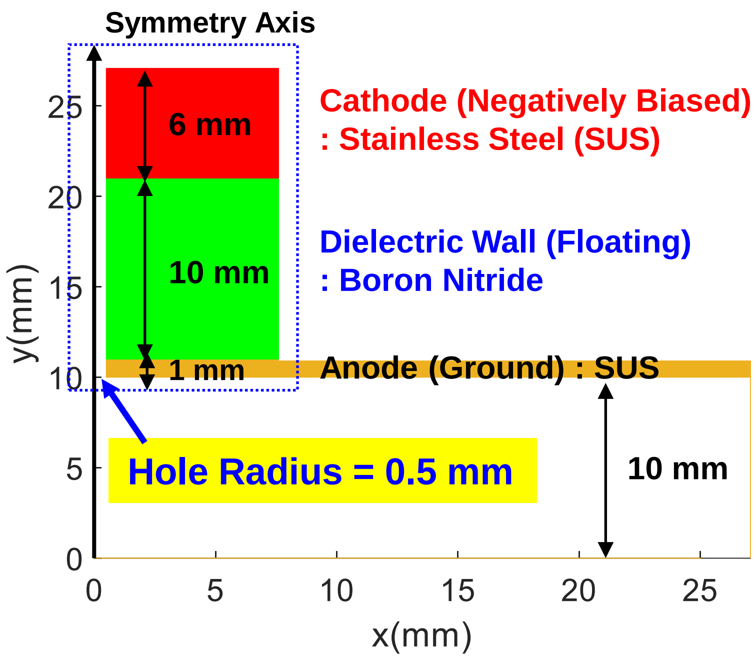
2D results when breakdown occurs

Simulation Domain



Cathode (Negatively Biased) : Stainless Steel (SUS)

Dielectric Wall (Floating) : Boron Nitride

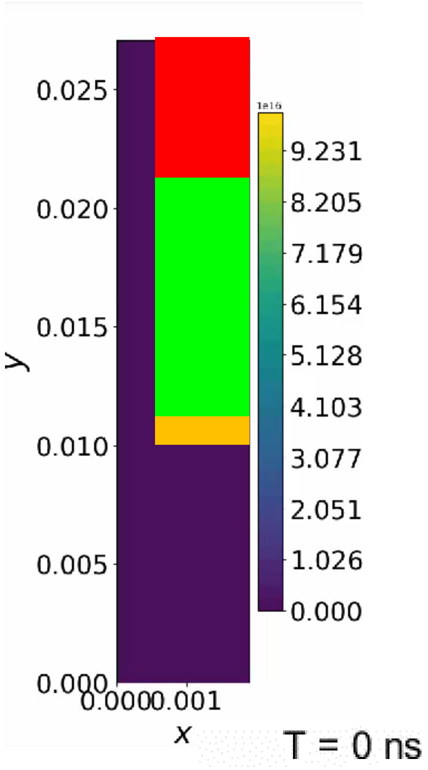
Anode (Ground) : SUS

Hole Radius = 0.5 mm

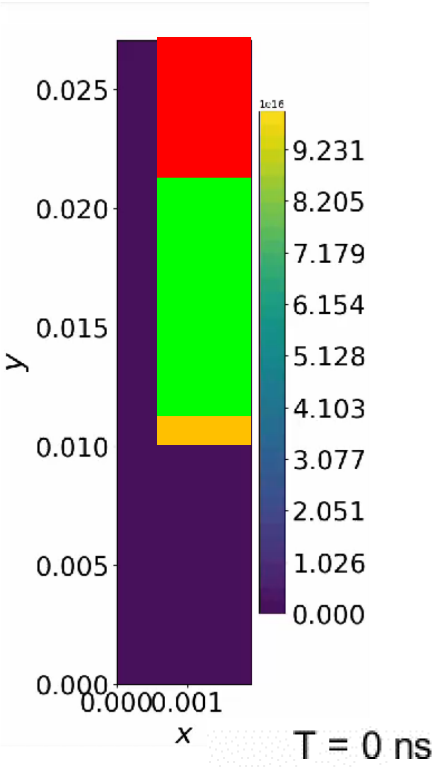
$\Delta x = 0.05$ mm / $\Delta t = 4$ ps

Cell # ≈ 10^5 (= 501 x 501)

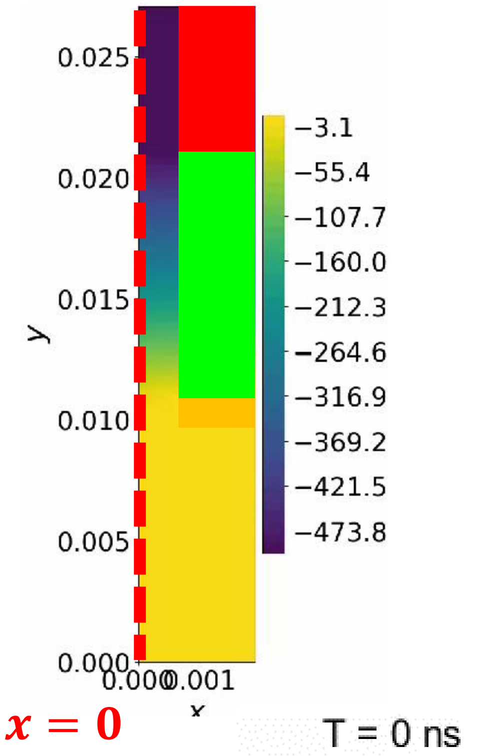
[Example] Simulation Result (Ar, 5 Torr, $V_{cat} = -500$ V, $n_0 = 10^{15}$)



n_i: 0 – 10^{17} (m^{-3})



n_e: 0 – 10^{17} (m^{-3})

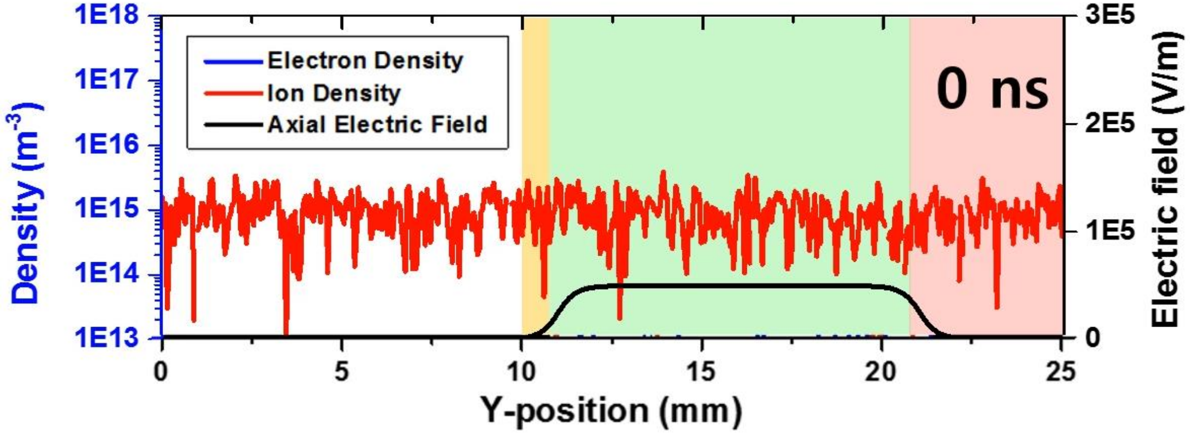


ϕ: –500 – 10 (V)

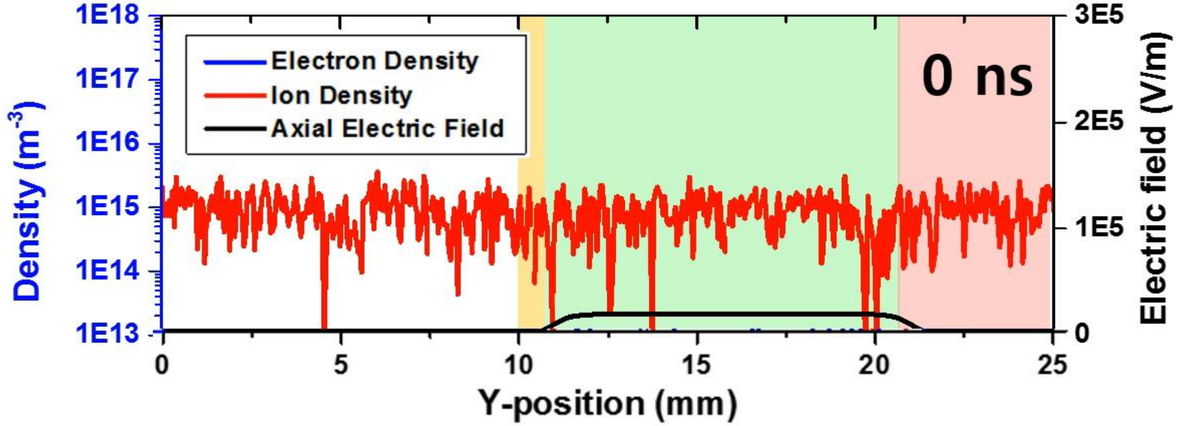
- Dramatic increase of the plasma density, the potential is screened out
  - Propagation of the breakdown inside the hole

1D results at centerline $x = 0$

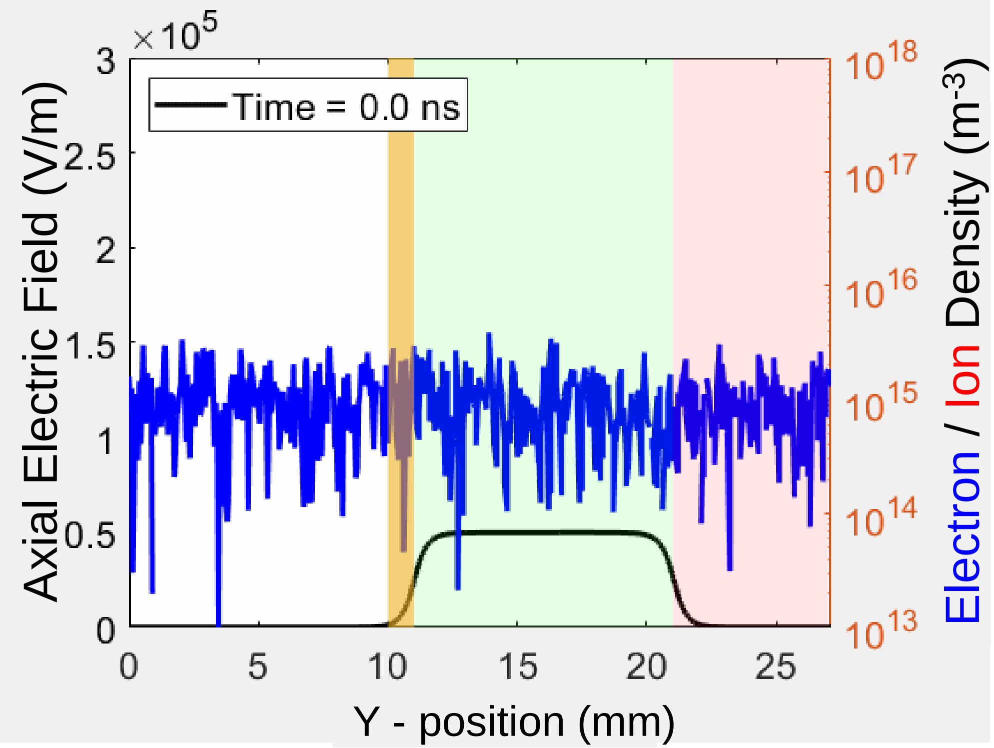
$V_{cat} = -500V$:breakdown



$V_{cat} = -150V$:No breakdown



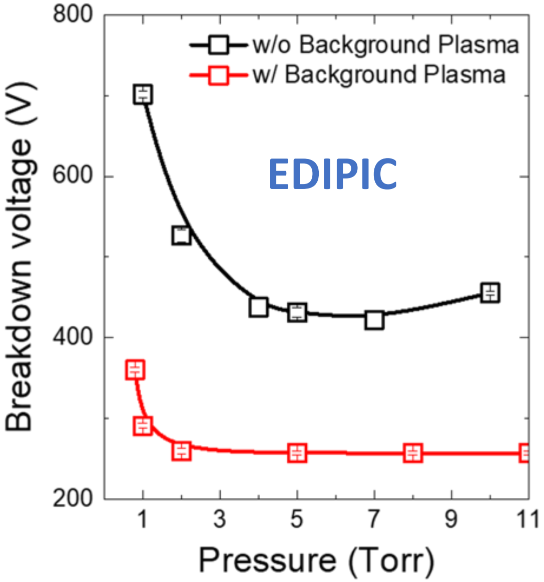
1D cuts at $x = 0$ with $P_n = 5\,\mathrm{Torr}, n_0 = 10^{15}\mathrm{m}^{-3}$



$P_n = 5\,\mathrm{Torr}, n_0 = 10^{15}\mathrm{m}^{-3}\ V_{cat} = -500V$

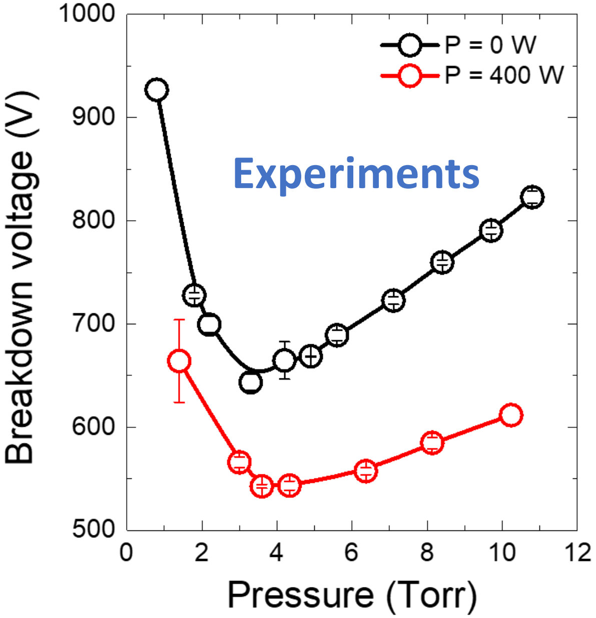
- An insufficient bias voltage does not trigger an electron avalanche
- Breakdown criterion: $n_i \uparrow + n_i \approx n_e$

Final Paschen curve



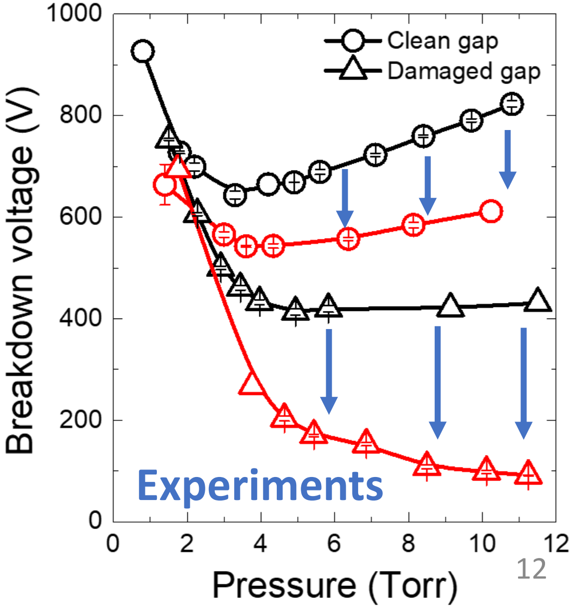
- ➢ Presence of background plasma lowers breakdown voltage: particle leakage distorts local E field and enhances ionization

- ➢ The trend of breakdown voltage in both EDIPIC and experiments is similar despite key differences:
  - ▪ Cartesian vs Cylindrical
  - ▪ BN vs Al2O3



Further study in progress with Cylindrical in EDIPIC + Alumina data

- ➢ Damaged gap = gap with previous breakdowns
- ➢ Crucial to prevent first breakdown from happening



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More info at poster session!

Our Development Team

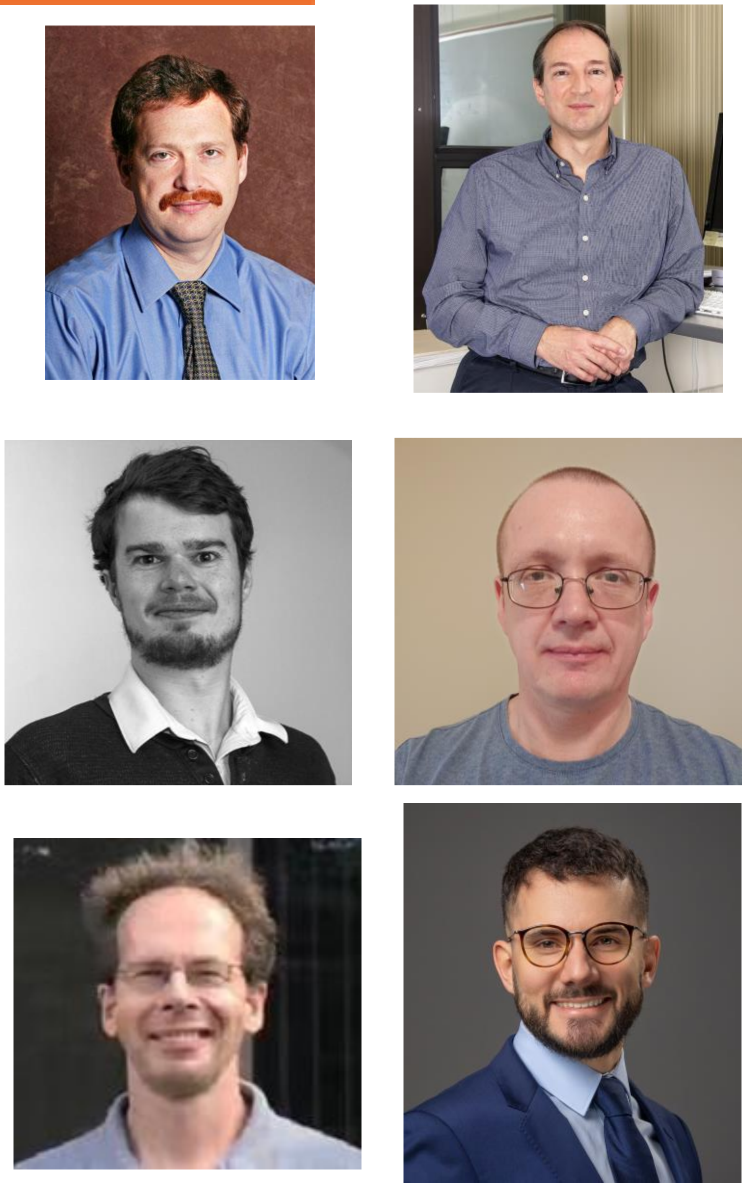
Igor D. Kaganovich, PI management,benchmarking, physics models

LTP-PIC:

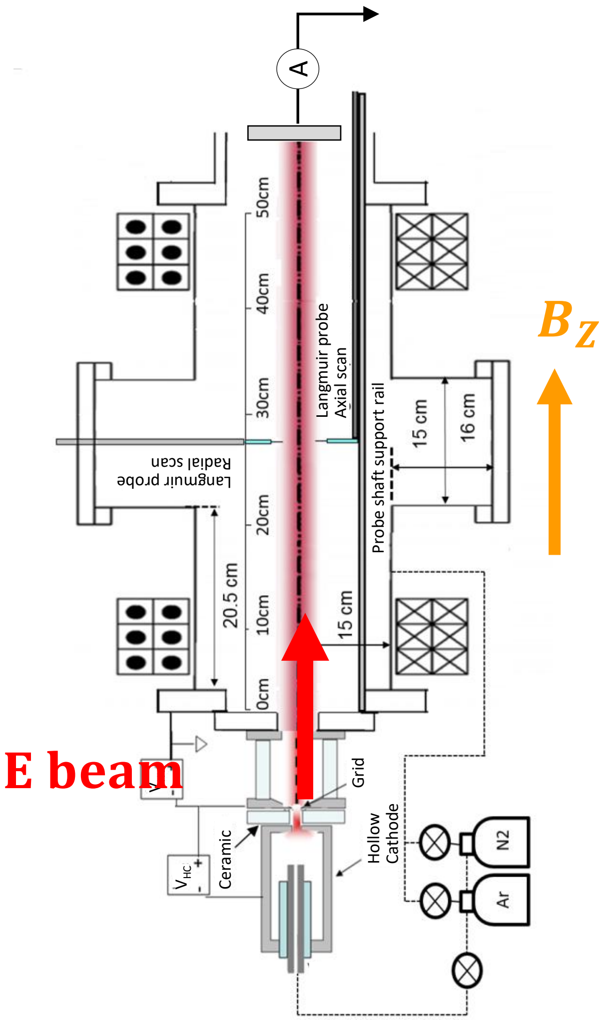
- **Stéphane Ethier, co-PI** porting the code to Heterogeneous CPU/GPU architectures.
- **Andrew (Tasman) Powis:** 3rd year postdoc, main LTP code developer.

2D EDIPIC:

- **Dmytro Sydorenko** Univ. of Alberta, original developer of EDIPIC since his Ph.D. thesis.
- **Alex Khrabrov, contractor**.
- **Willca Villafana** 2nd year postdoc



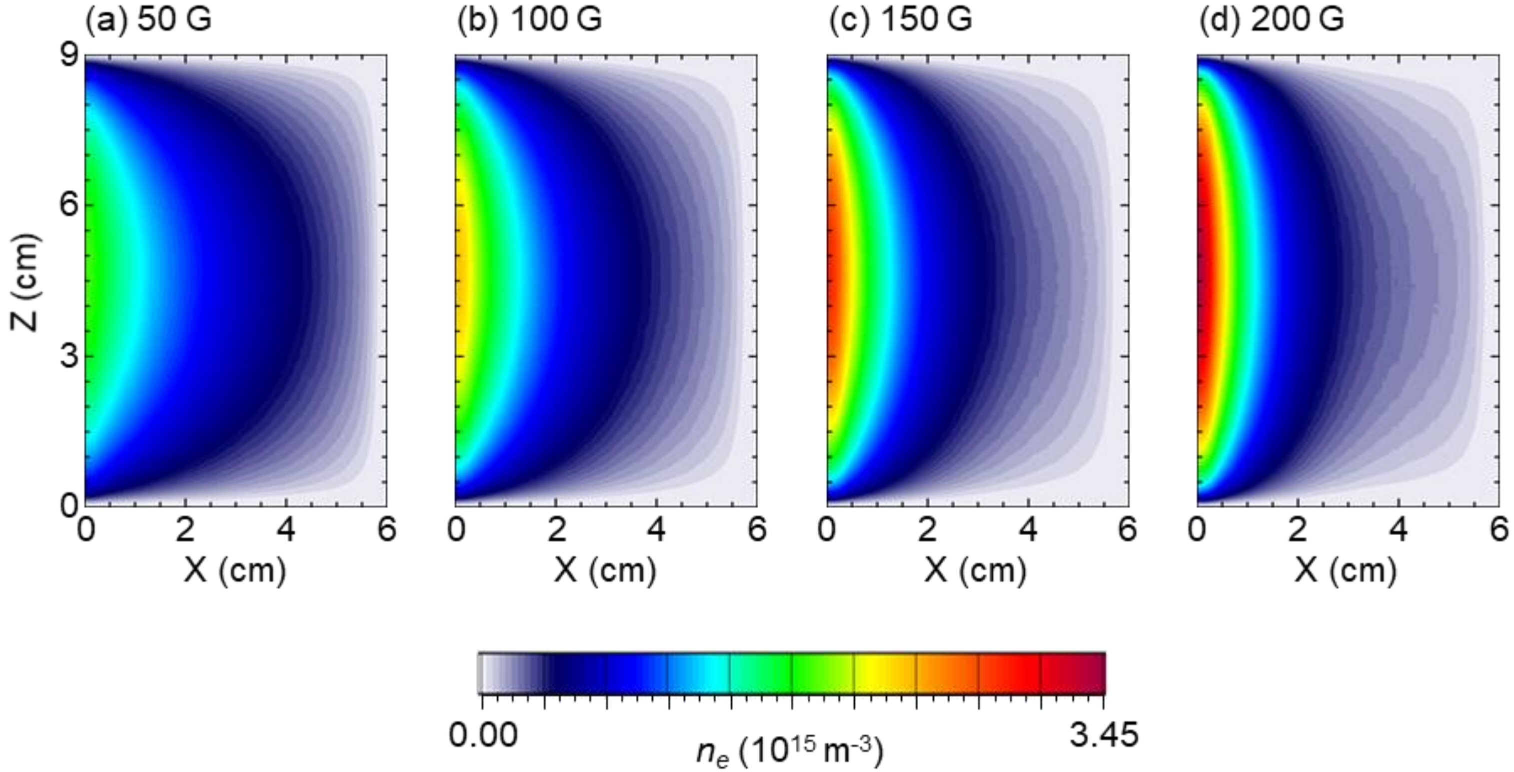
Electron-beam-generated plasma



Schematic of NRL experimental set up Ar, 20 mT, xx G, 12.5 mA/m, 2 keV electron beam

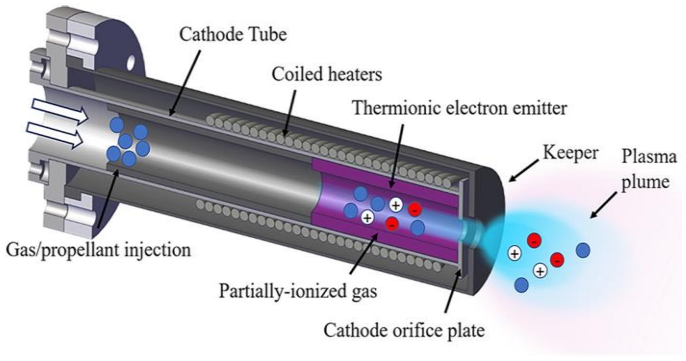
10 – 40 mTorr gas pressure
0 – 200 G magnetic field

n_e

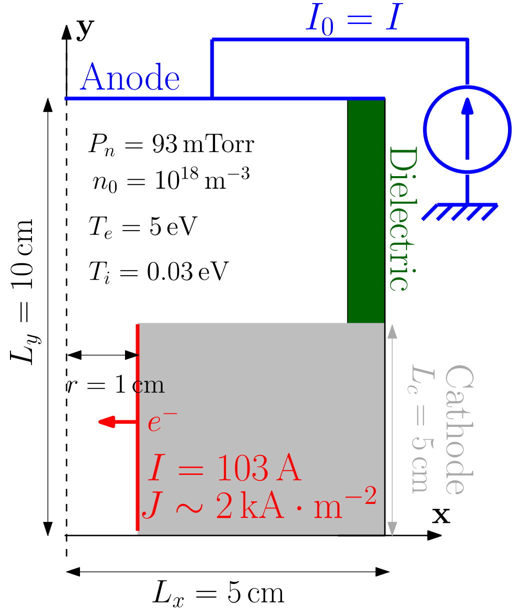


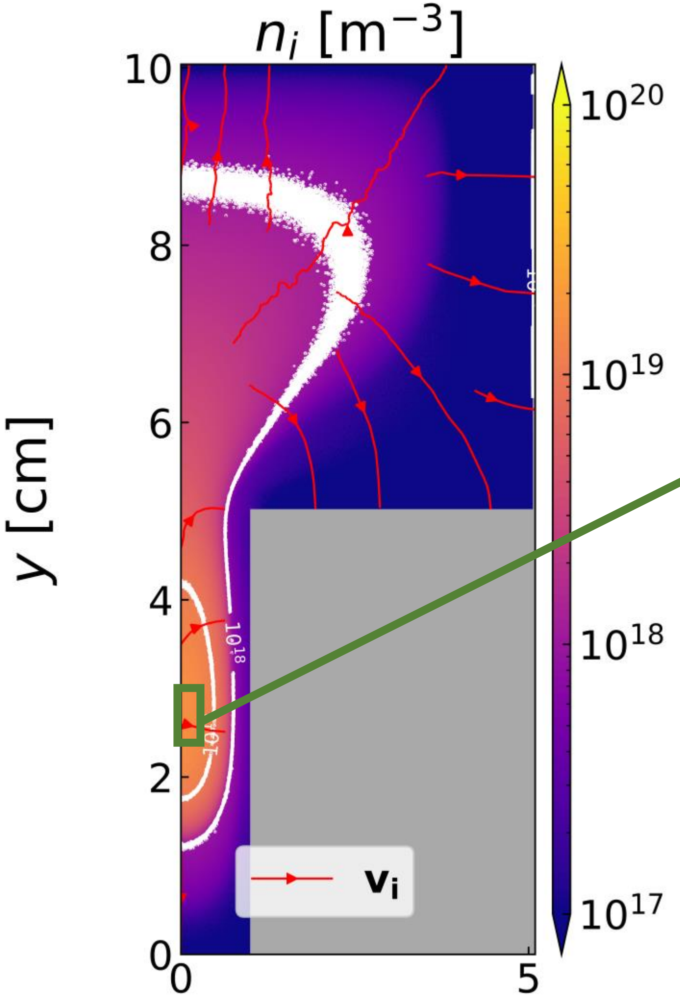
[1] S. Rauf, D. Sydorenko, S. Jubin, W. Villafana, S. Ethier, A. Khrabrov, and I. Kaganovich, “Particle-in-cell modeling of electron beam generated plasma,” Plasma Sources Sci. Technol. **32**(5), 055009 (2023).

Hollow cathode system

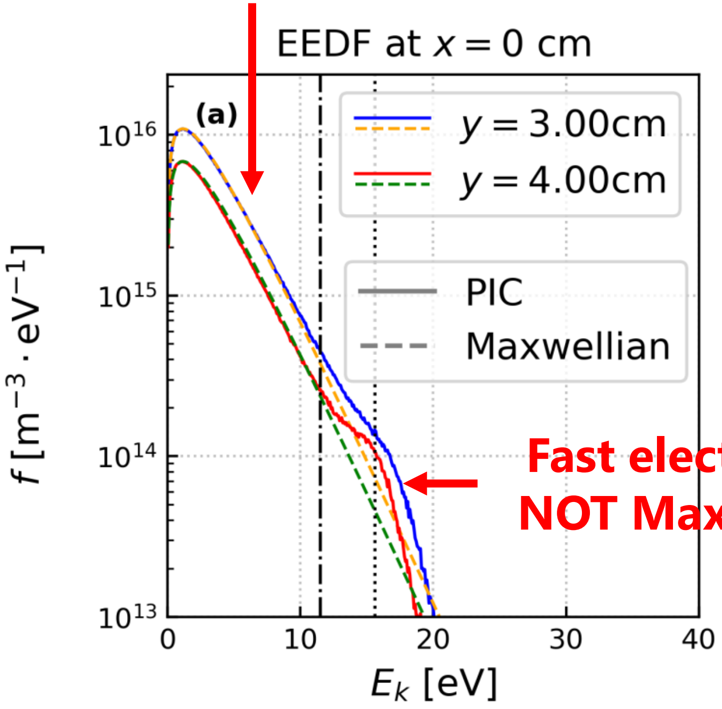


Schematic of hollow cathode [1]





Maxwellian

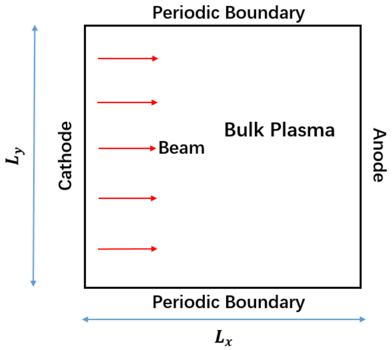


Fast electrons = NOT Maxwellian

Hollow cathode exhibits non Maxwellian EEDF

Electron-beam plasma interaction

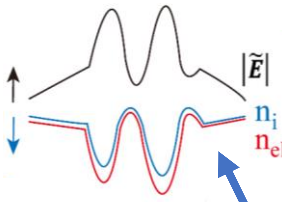
57 PIC simulations varying energy and density of the beam E_b and n_b



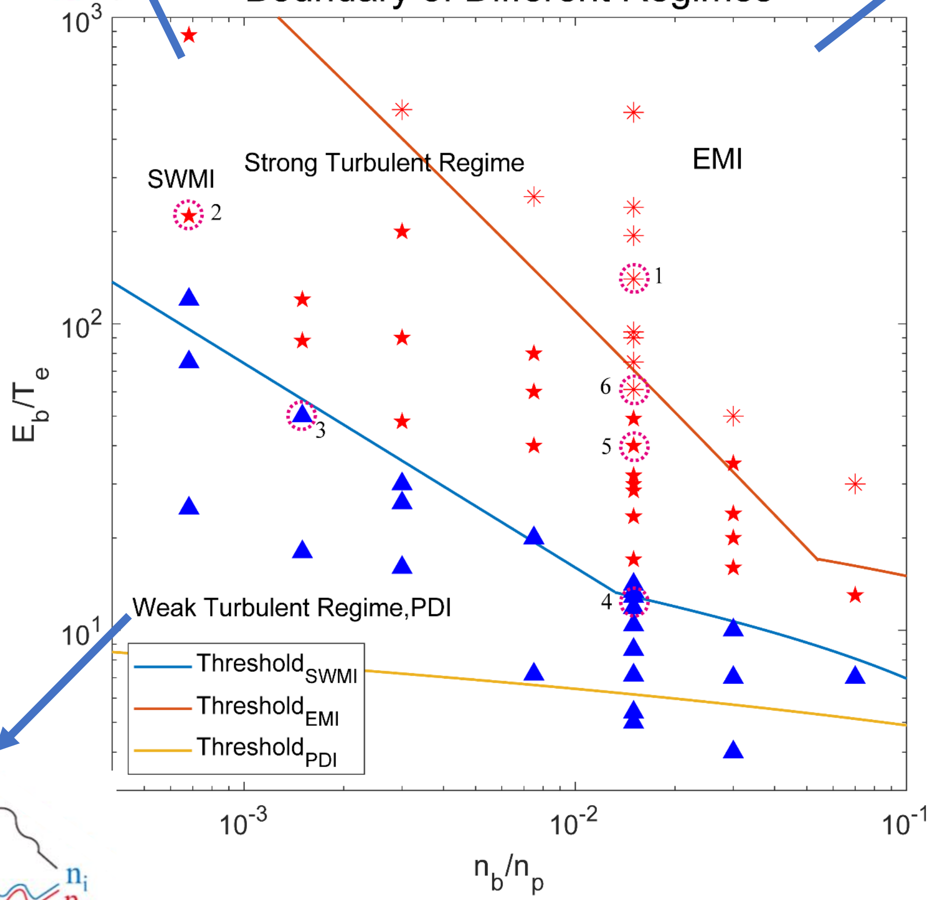
PDI (parametric decay instability): generating backward waves (waves slightly perturb plasma)

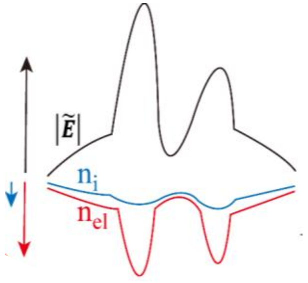
SWMI (standing wave modulational instability): localized standing waves

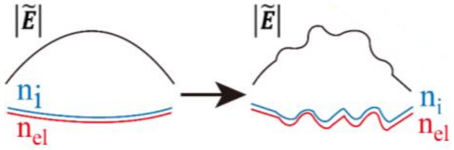
EMI (*electron modulational instability*): rapidly growing standing waves (breaks quasineutrality). **NEW**



Boundary of Different Regimes







[Haomin Sun, et al, Phys. Rev. E **106**, 035203, (2022)]
[Haomin Sun, et al, Phys. Rev. Lett. **129**, 125001, (2022)]

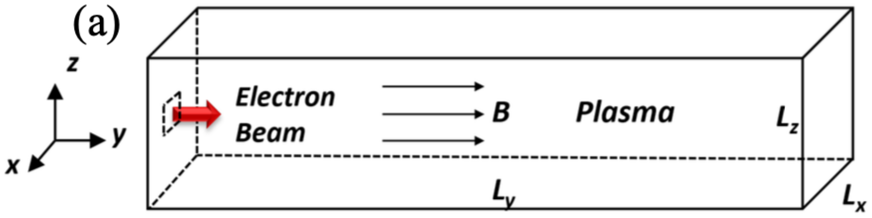
Our PIC code LTP PIC

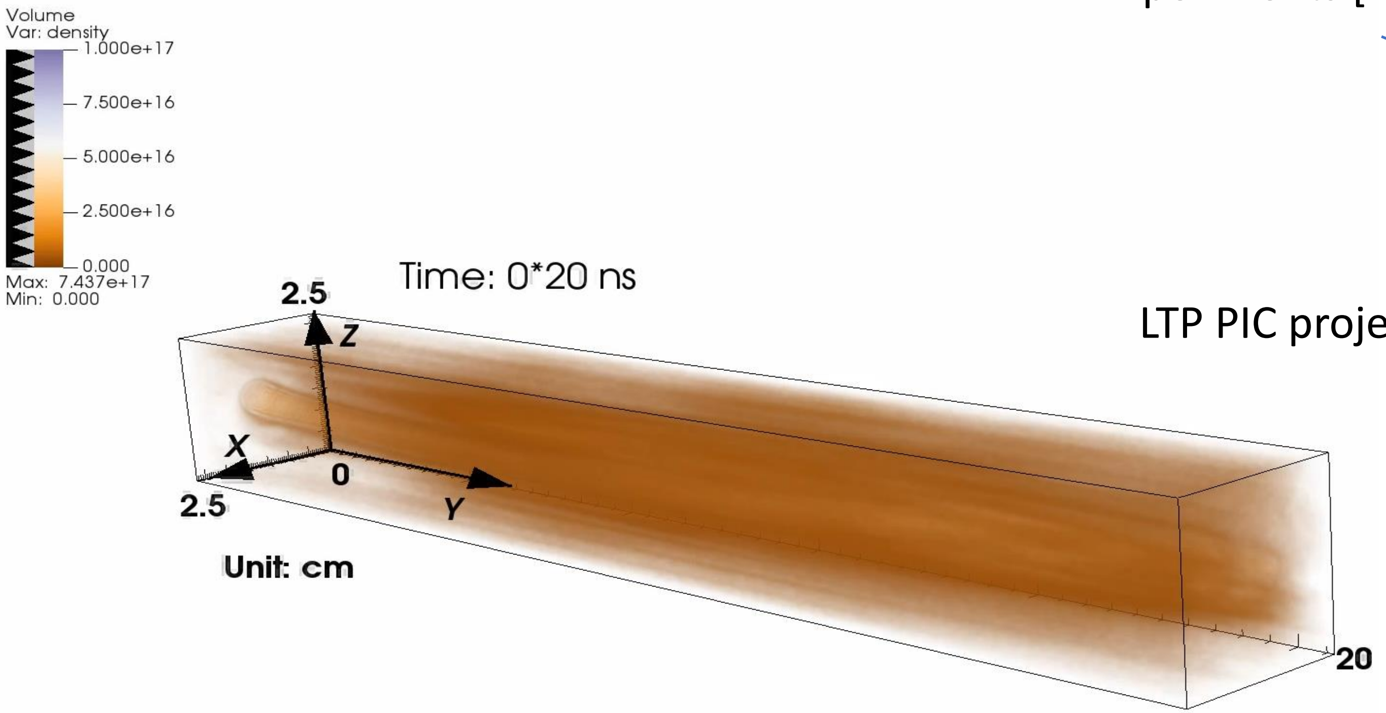
- Main features
  - ✓Explicit 2D-3D/3V electrostatic PIC in uniform cartesian geometry
  - ✓Written in C-C++, runs on CPUs **accelerated with GPUs** via OpenAcc
  - ✓Monte-Carlo model of electron-neutral and ion-neutral collisions
  - ✓Field solve via Geometric Multigrid algorithms from the Hypre package (LLNL)
  - ✓Python + *VisIt* software as post-processing tools
- Written from the ground up for scalability:
  - ✓Inter-node parallelization via *MPI*
  - ✓Intra-node parallelization via *MPI* and/or *OpenMP*
  - ✓Elimination of inner loop logic to take advantage of vector registers

Portable code and soon available to the community to simulate large 2D/3D simulation domains

3D spoke-like activity in a Penning discharge

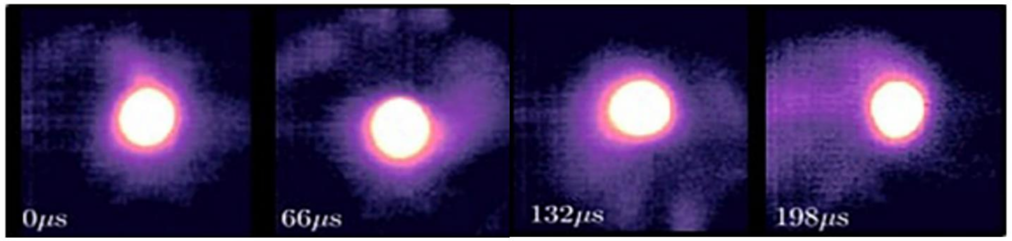
Partially magnetized ExB discharges, widely used in industry and research, often exhibit large-scale, low-frequency, **coherent structures known as "spokes"** [1,2].



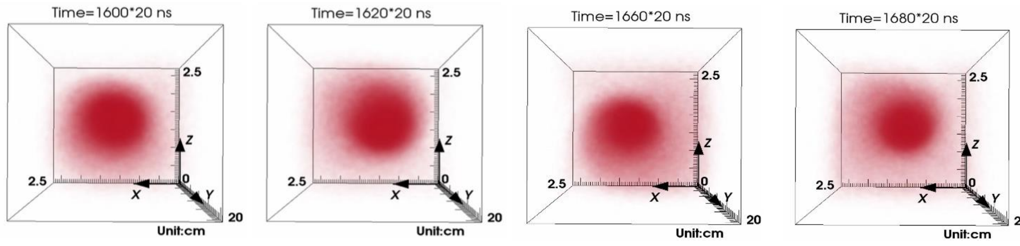


The experiments exhibit qualitatively similar behavior, with a rotation velocity similar to that observed in experiments.

Experiments [1]



LTP PIC projection



[1] E. Rodriguez, et al. Physics of Plasmas 26, 053503 (2019).

[2] A. Escarguel, The European Physical Journal D 56, pg. 209-214 (2010).

Conclusion

- ✓ **Breakdown:** experimental and PIC study (**PCRF**). Background plasma and previous breakdowns facilitate future breakdowns

- ✓ **EDIPIC-2D** is an **open source extensively verified** PIC code routinely used by the industry and academia for a wide variety of LTP systems. Example of applications: **CCP, ICP, e-beam, hollow cathode, ECR, Hall thruster, Penning discharge, etc … Realistic configuration with external circuit and inner objects. 10+ publications**

- ✓ **LTP-PIC** is a 2D/3D PIC designed for HPC aiming for whole-device modeling. **Excellent scalability up to hundreds of GPUs for large and more realistic geometries.**

Questions?

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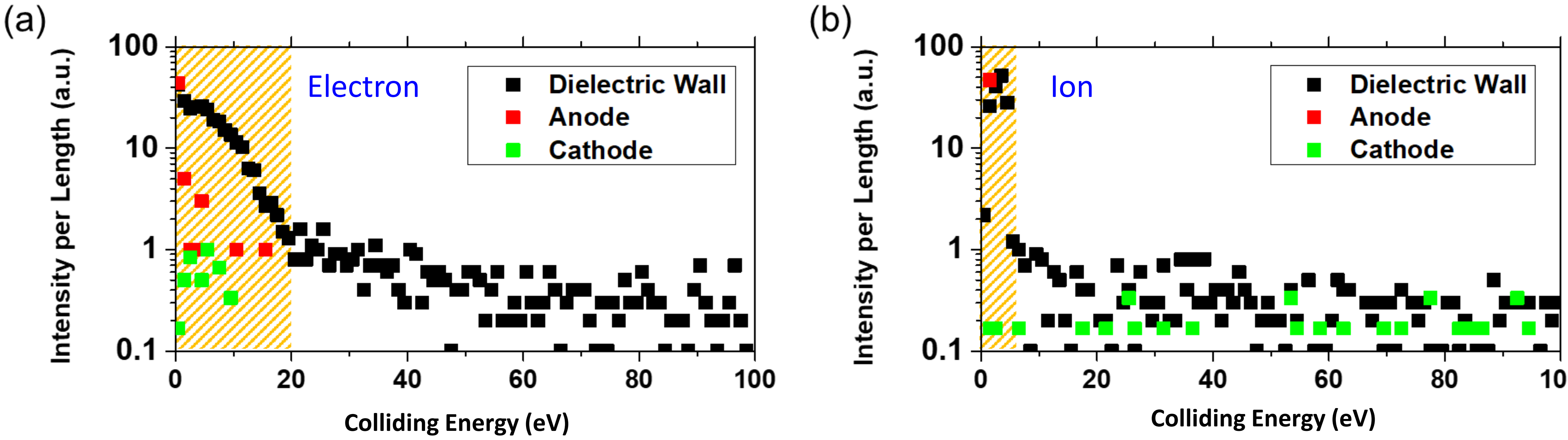
More info at poster session!

Questions?

Analysis of SEE: the γ process

- ➢ Recorded normalized energy spectrum of particles hitting the walls

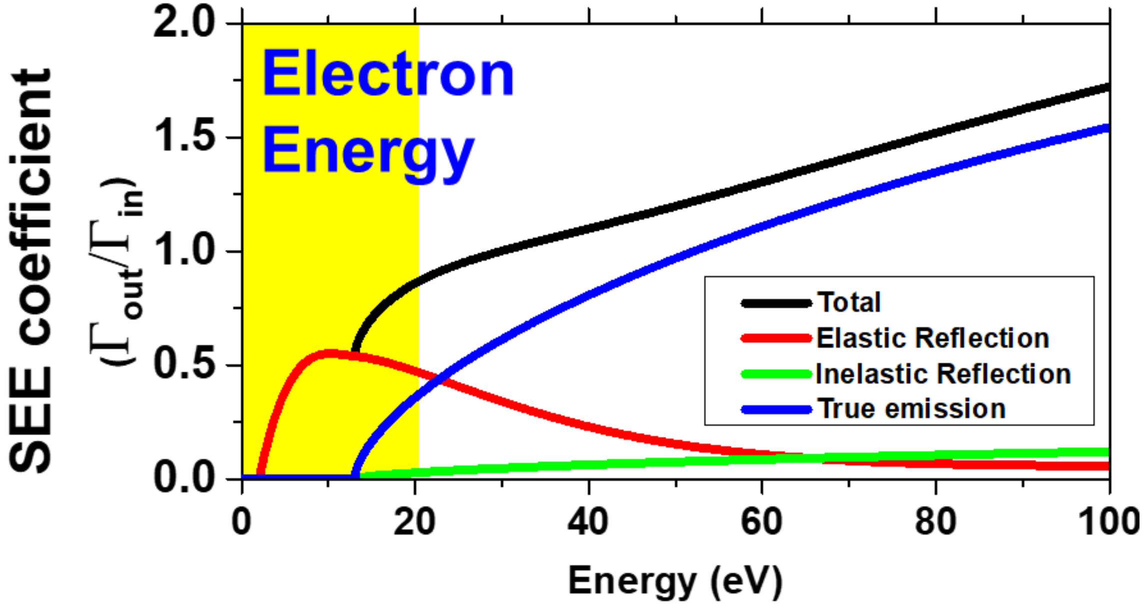
$$n_0 = 10^{15}\mathrm{m}^{-3}, V_{cat} = -500\mathrm{V}$$



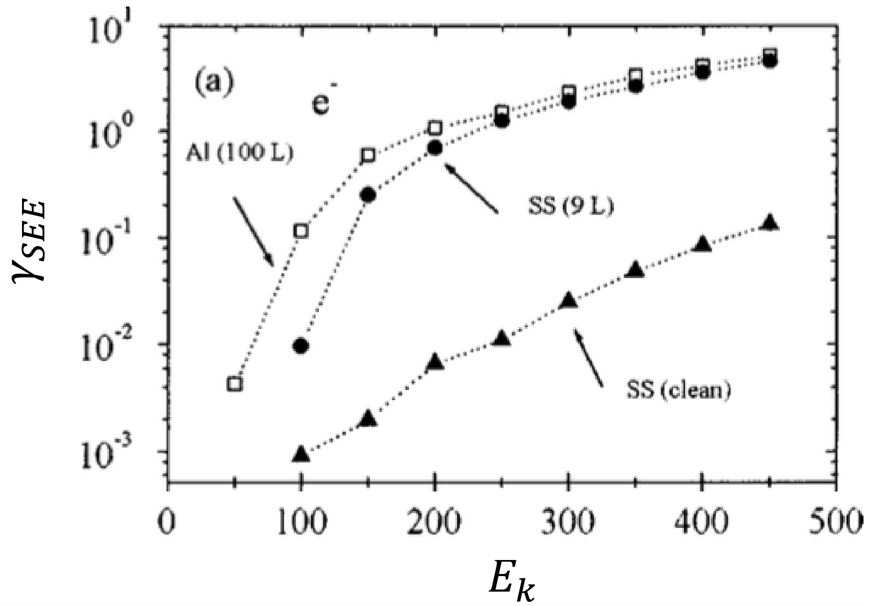
➢ Most electrons and ions hit the dielectric at low energy

Analysis of SEE: the γ process

- Electron-induced SEE yield for BN is based on the fitted Vaughan's model [1,2]



- Ion-induced SEE yield from stainless steel is below <0.1 [3,4]

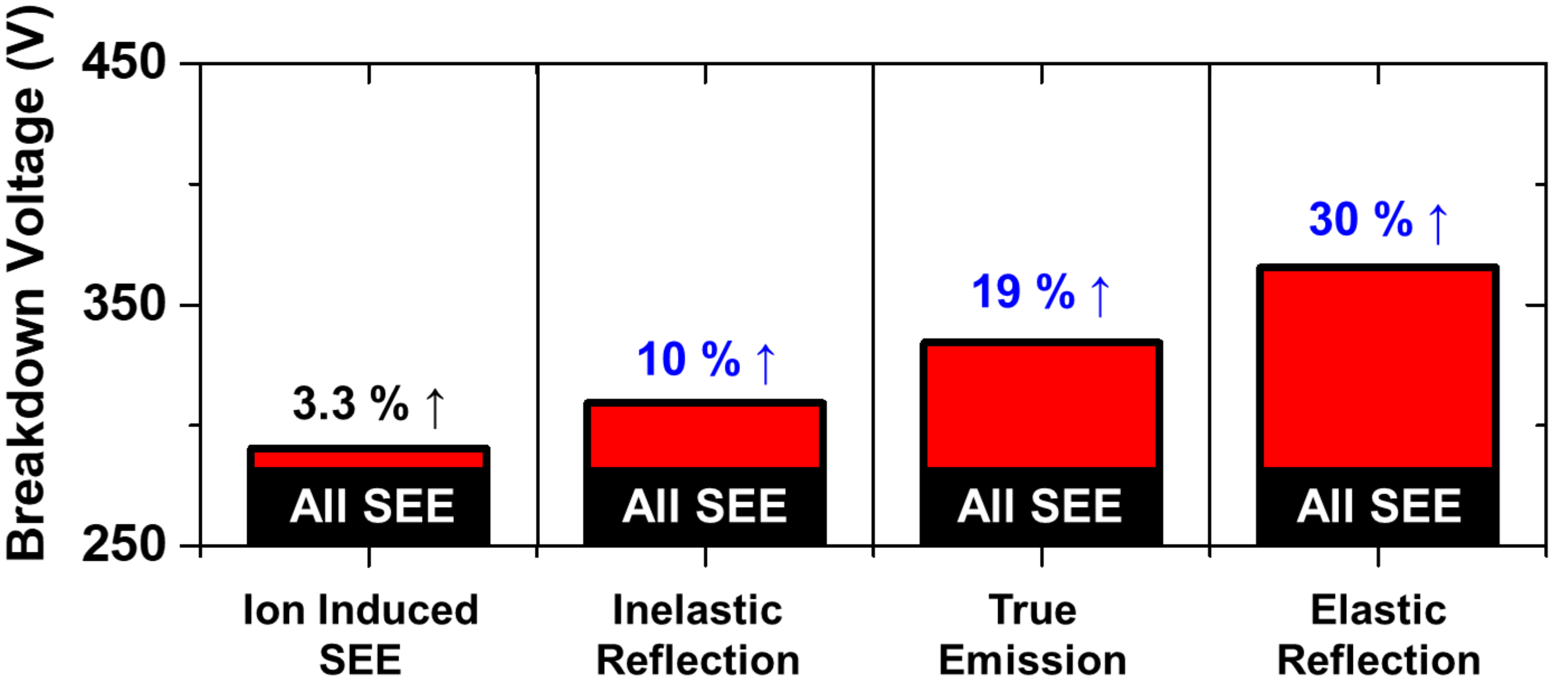


- A significant portion of SEE electrons is incident electrons reflected elastically
- Ion-induced SEE electrons from the cathode are less important in contrast to what is typically reported in the literature [5]

[1]D. Sydorenko, PhD thesis (2006)
[2] M. Villemant, *et al.* EPL **127**(2), 23001 (2019).
[3] A.V. Phelps, and Z.L. Petrovic, Plasma Sources Sci. Technol. **8**(3), R21–R44 (1999)
[4]S.G. Walton, *et al.,* Journal of Applied Physics **85**(3), 1832–1837 (1999)
[5]J.Y. Kim, Plasma Sources Sci. Technol. **31**(3), 033001 (2022)

Analysis of SEE: the γ process

- ➢ Variation of the breakdown voltage if the SEE yield is turned off

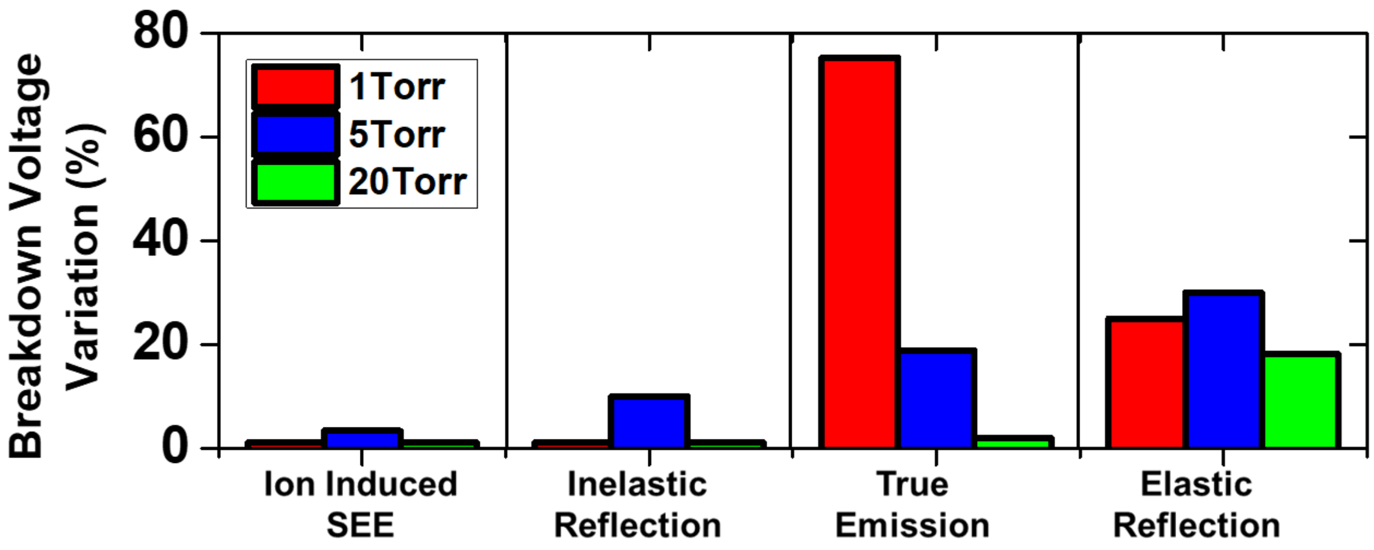


E.g., if elastic reflection in SEE is turned off, $V_{breakdwon}$ goes up by 30% with respect to the baseline ("All SEE")

- ➢ True SEE and Elastic Reflection are the most important

Analysis of SEE: the γ process

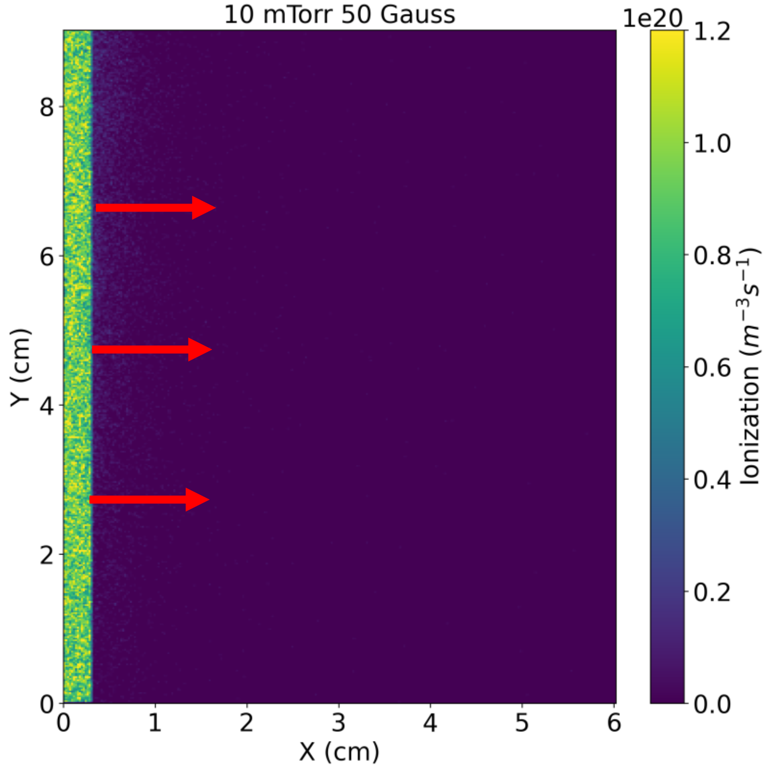
- Variation of breakdown voltage if SEE yield is turned off is dependent on pressure

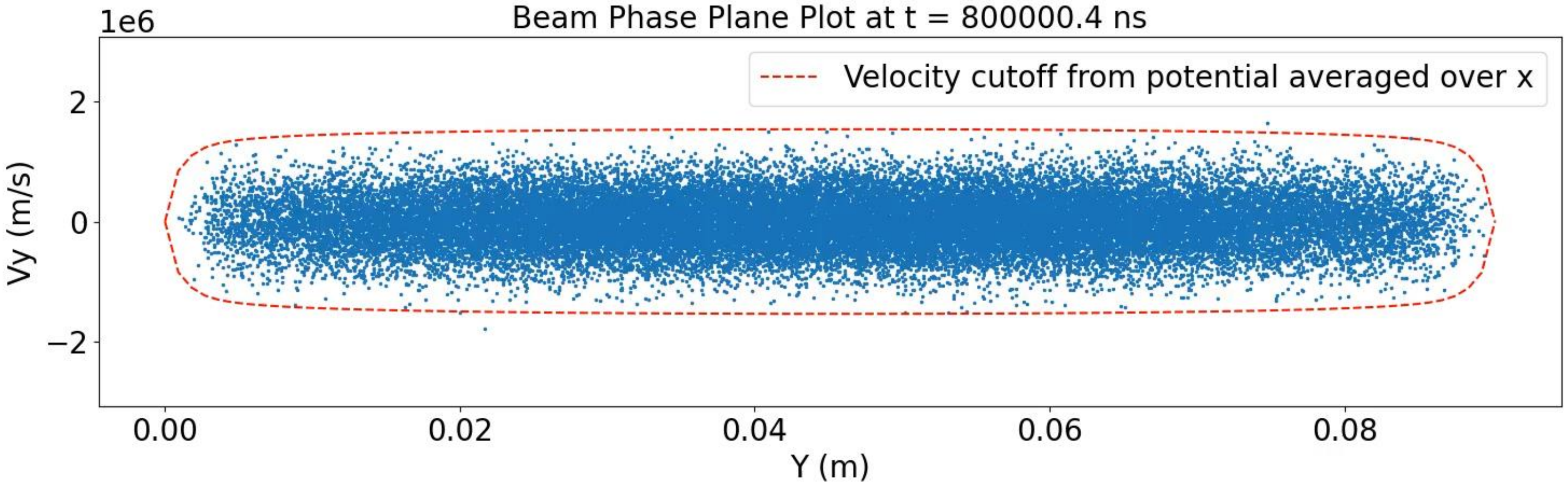


- True SEE more important at low pressure because electrons are faster (less collisions)

Electron-beam-generated plasma

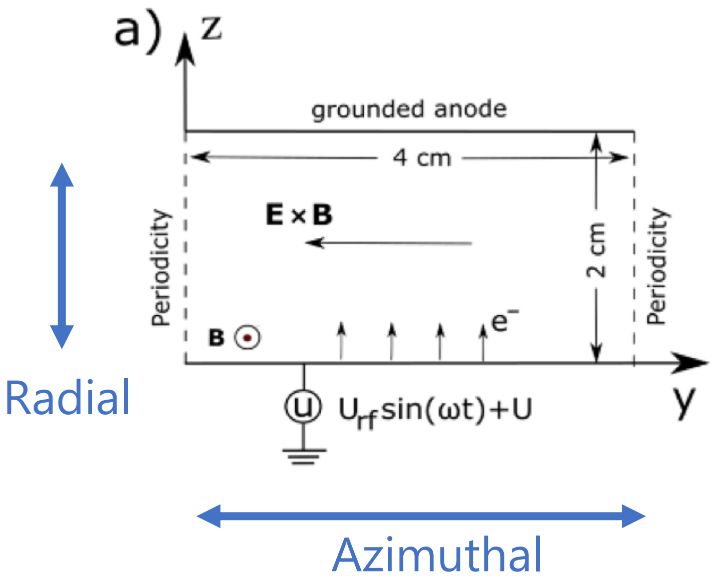
- The ionization zone is confined to the beam area



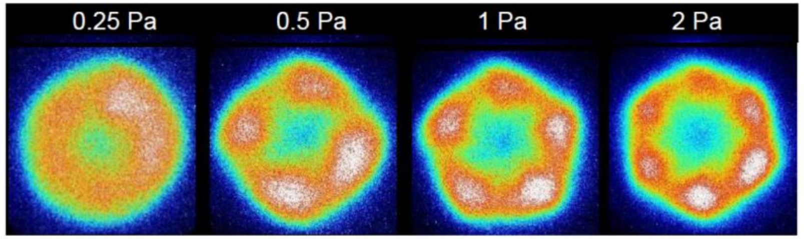


- Cold electrons are trapped in potential well. Fast, 2keV electrons escape
- Non ambipolar diffusion in x direction

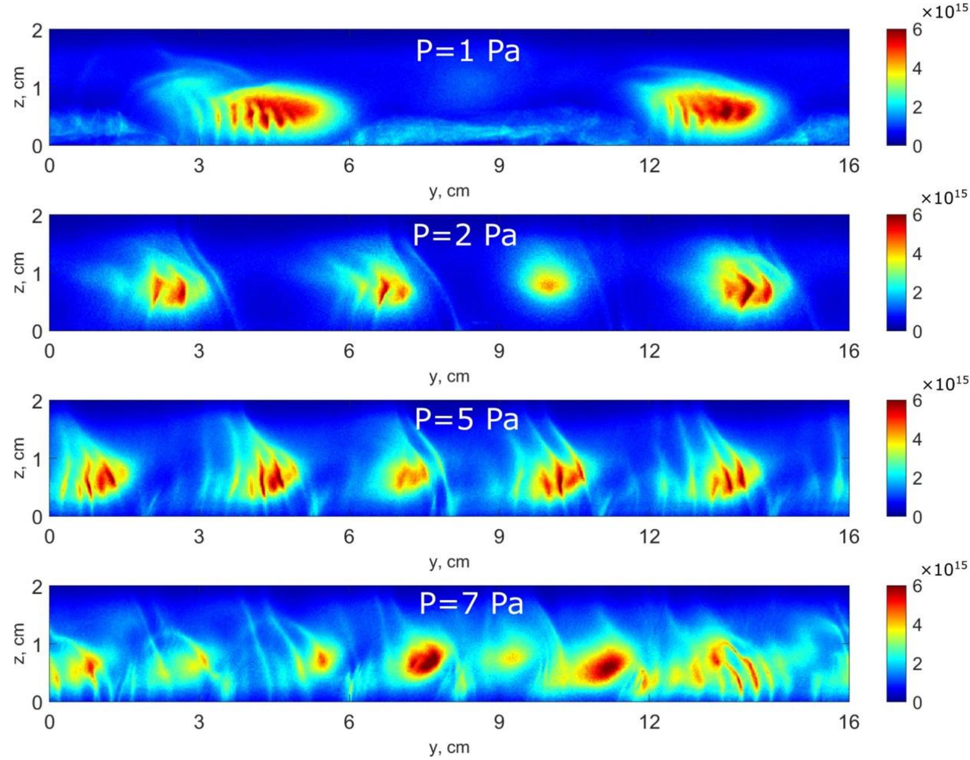
Rotating spokes in RF CCP



Experiments



EDIPIC results



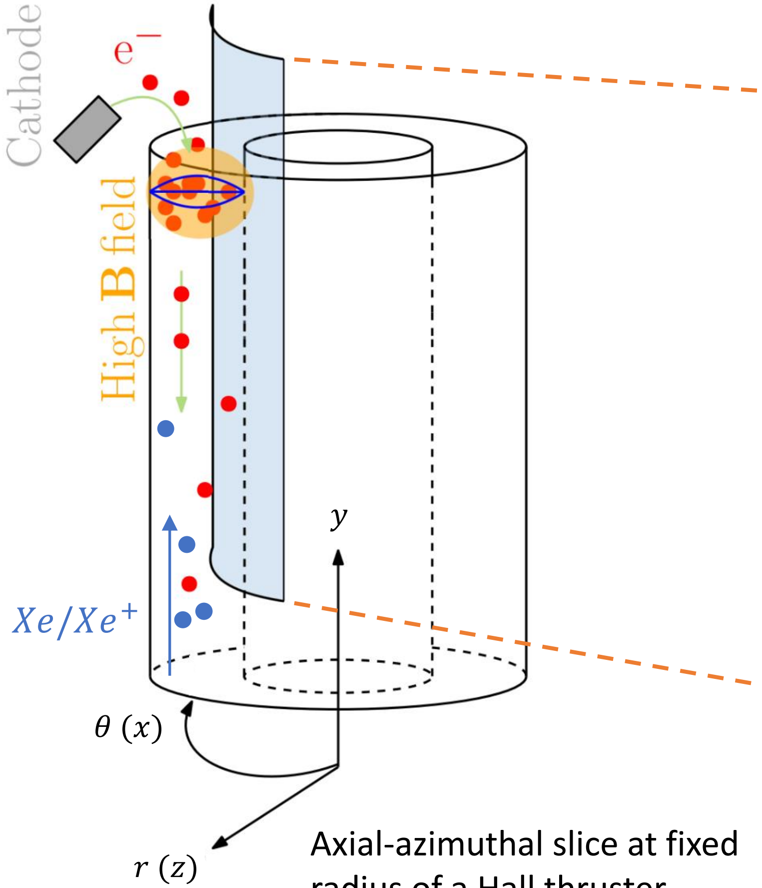
Similar trend in both PIC and experiments.

[1] L. Xu, H. Sun, D. Eremin, S. Ganta, I. Kaganovich, K. Bera, S. Rauf, and X. Wu, “Rotating spokes, potential hump and modulated ionization in radio frequency magnetron discharges,” Plasma Sources Sci. Technol. **32**(10), 105012 (2023).

Talk Overview

1. Context and motivation
2. Modeling capabilities using EDIPIC-2D
3. Toward 3D whole-device modelling with LTP-PIC
4. Advanced algorithms

3D simulation of Hall thruster channel



Axial-azimuthal slice at fixed radius of a Hall thruster channel [Villafana 2023]

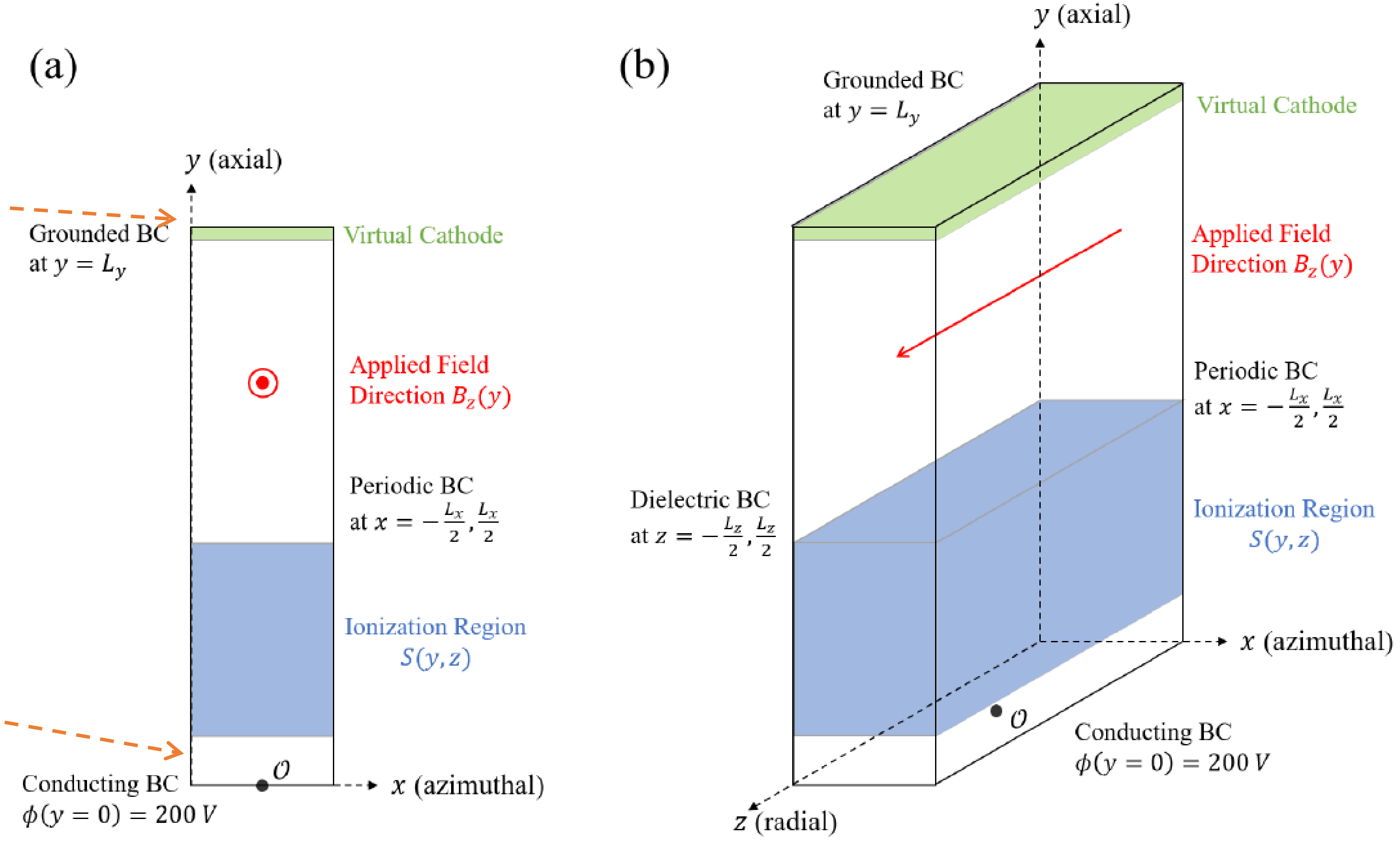
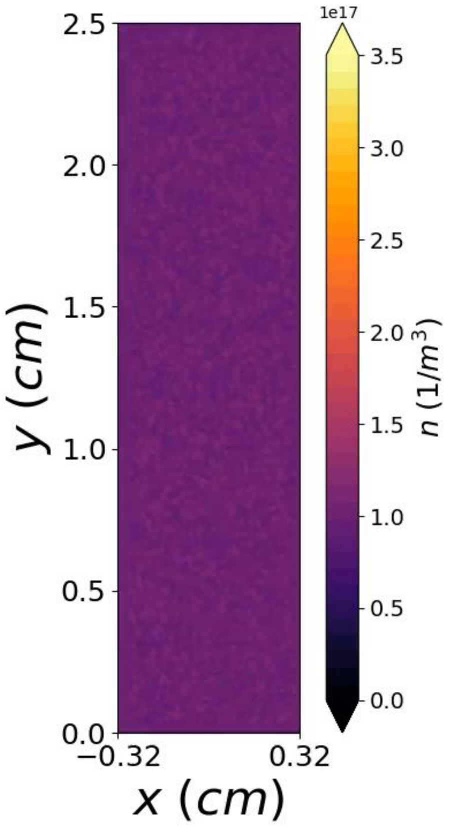
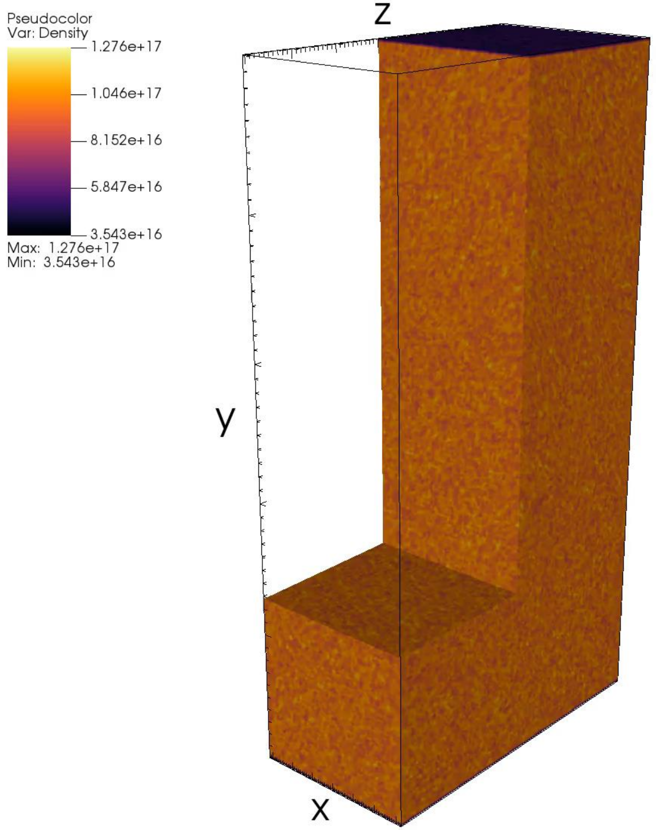
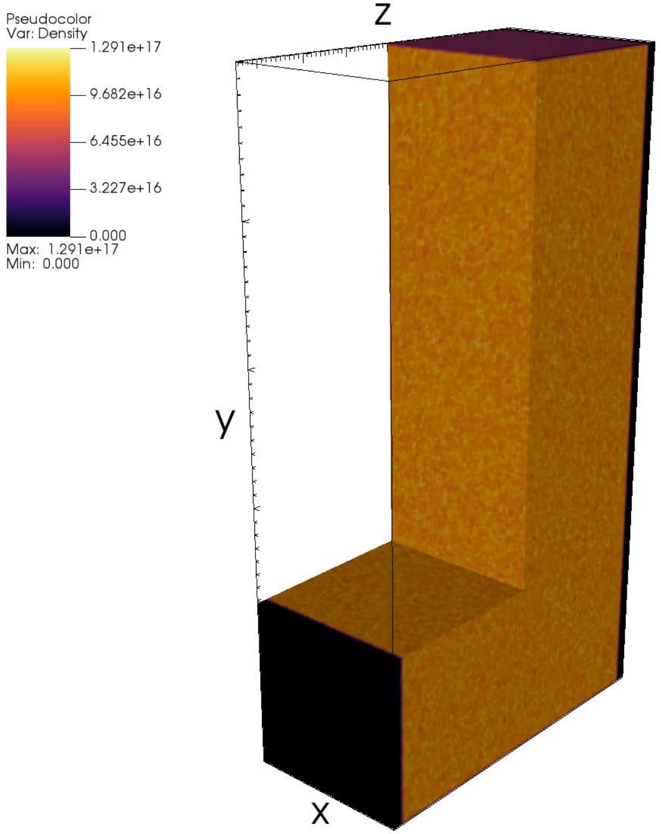


Fig. 1 Schematic of the simulations, with (a) showing the configuration for the modified Landmark 2a benchmark and (b) the configuration for the 3D simulations extended into the radial direction.

3D simulation of Hall thruster channel


2D

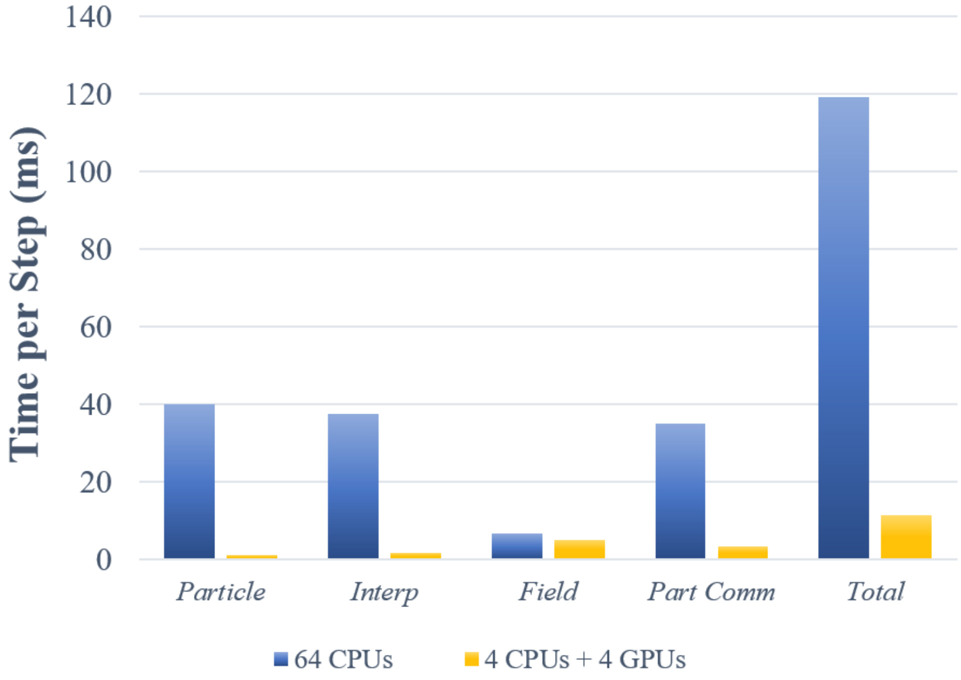

3D Periodic


3D Dielectric

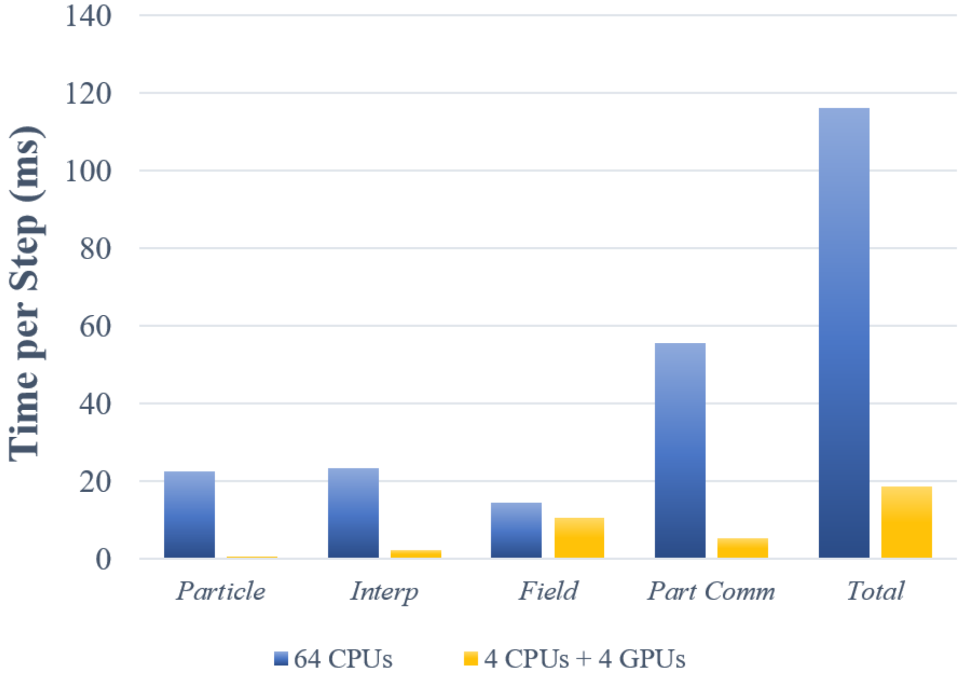
Different electron transport in 3D.
Influence of boundary conditions

Performance of LTP PIC

<u>2D simulations</u>
$8{,}192^2$ cells with
1,000 particles-per-cell
256 nodes



<u>3D simulations</u>
256^3 cells with 1,000
particles-per-cell
128 nodes



Performance of LTP PIC

2D simulations
$8{,}192^2$ cells with
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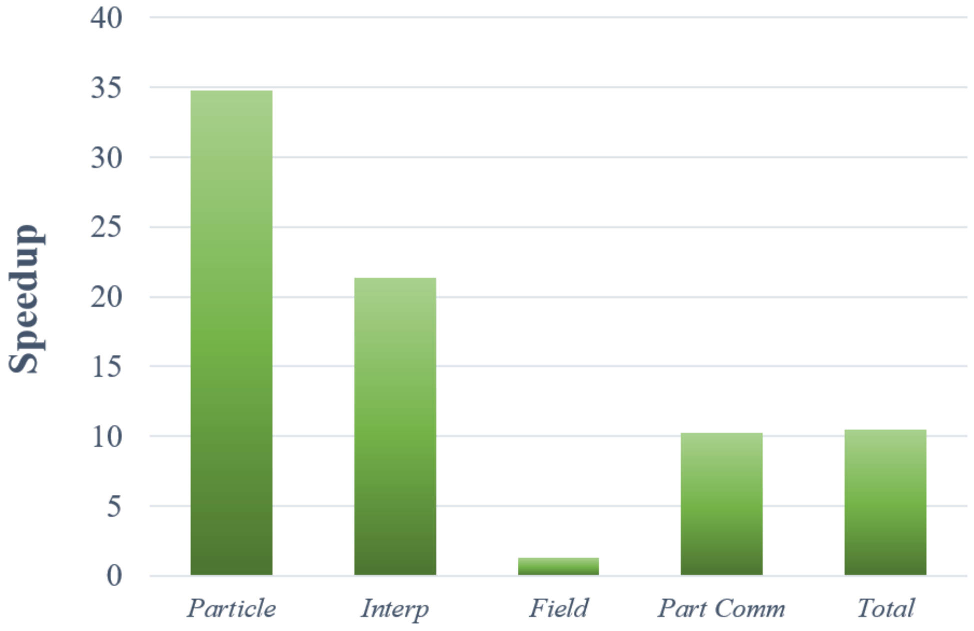

3D simulations
256^3 cells with 1,000
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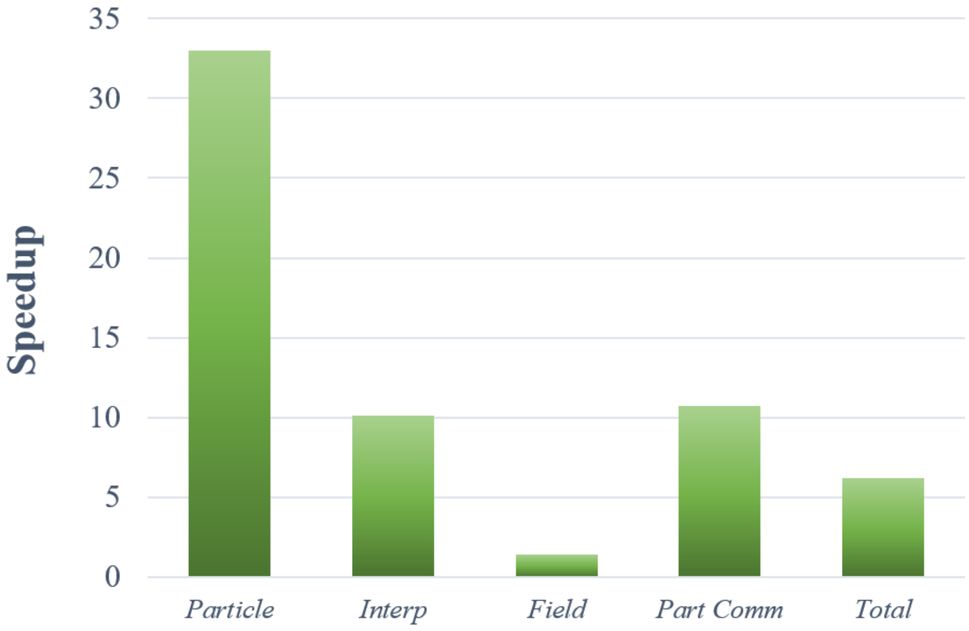
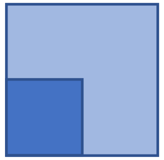
128 nodes



Performance of LTP PIC

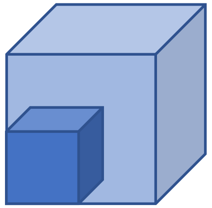
Weak scaling = load on resources remains the same while increasing the size of the domain

2*D*

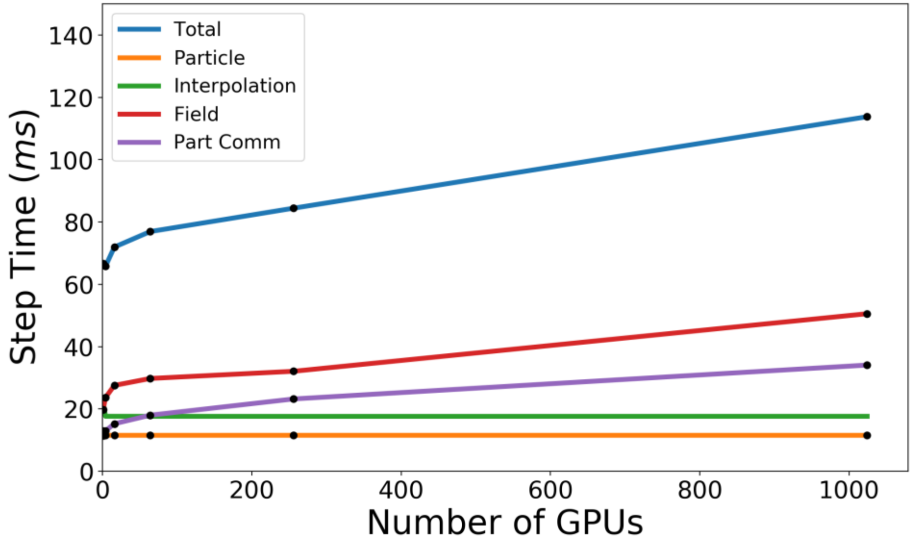


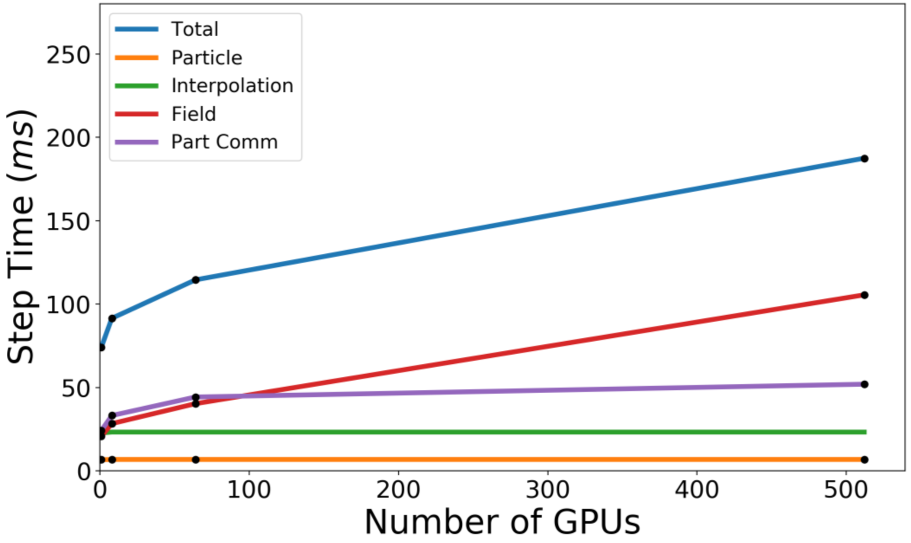
256^2 cells and
1,000 particles-
per-cell per GPU

3*D*



32^3 cells and
1,000 particles-
per-cell per GPU



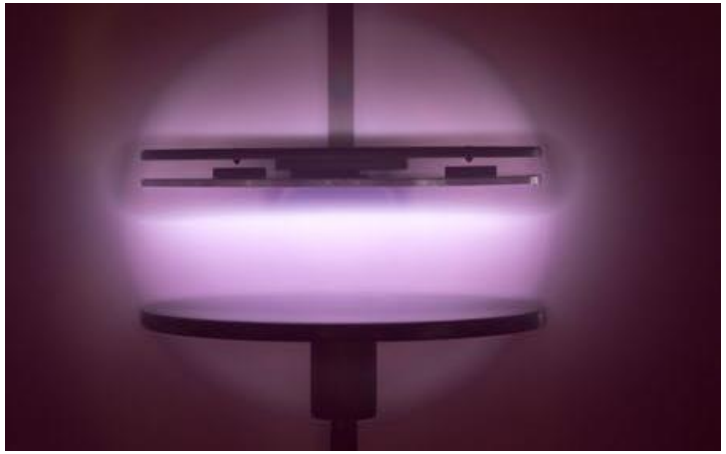


Domain x500 but efficiency decreases by only x1.5 = **large computational domain/geometry**

Can we model the whole device?

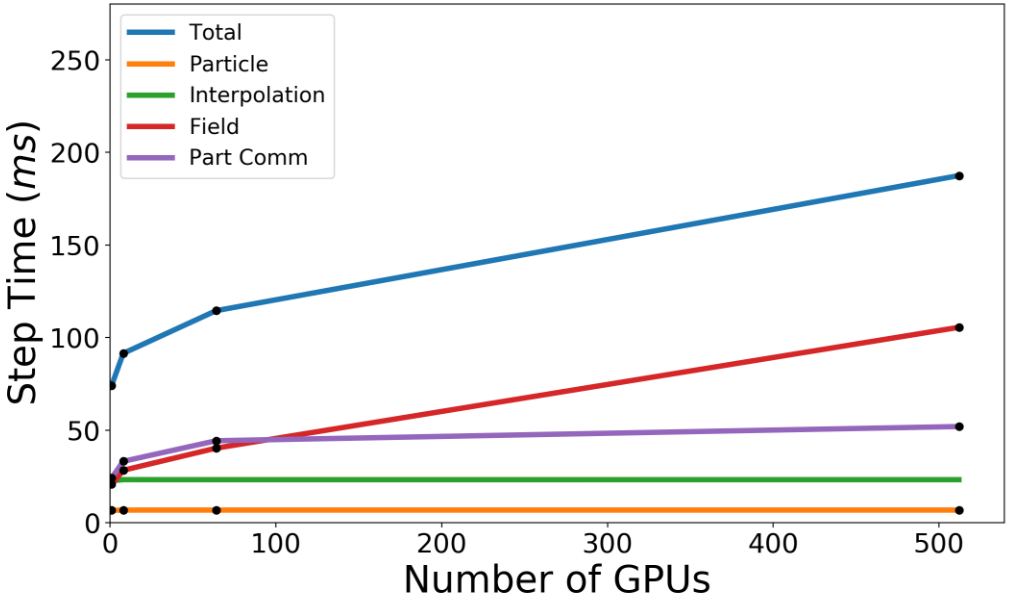
To model our etching device in 3D-3V, we require:

- 10^8 cells (10x10x5 cm^3)
- 10^{11} simulation particles
- 10^8 time steps



Each time step is approximately $100\ ms$ for a large 3D simulation

If we require 10^8 time steps this corresponds to a simulation > 100 days!



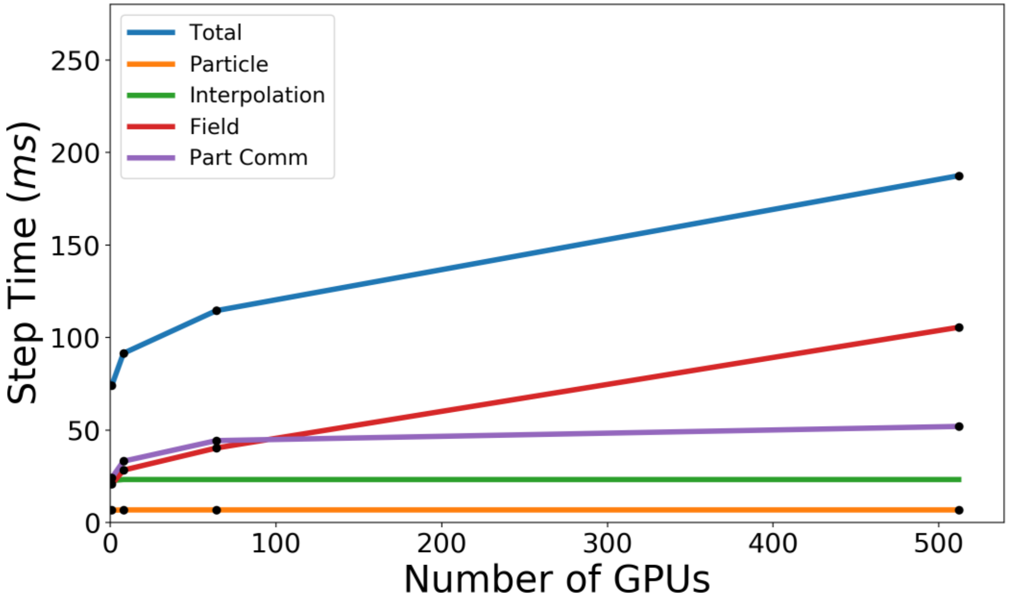
Weak scaling of LTP-PIC in 3D

Can we model the whole device?

We think a goal of 10 days is potentially useful to industry

We can improve step time in three ways:

- More resources
- Better computer science
- New algorithms



Weak scaling of LTP-PIC in 3D

Backup

Talk Overview

1. Context and motivation
2. Modeling capabilities using EDIPIC-2D
3. Toward 3D whole-device modelling with LTP-PIC
4. Advanced algorithms

2D simulation of CCP

- 2D, 30 mTorr Argon discharge
- 4000×1000 cells, ≈ 500 particle-per-cell, 20 million time steps
- Simulated using 256 GPUs on the *Perlmutter* supercomputer in 6 days

Fig. Simulation geometry,

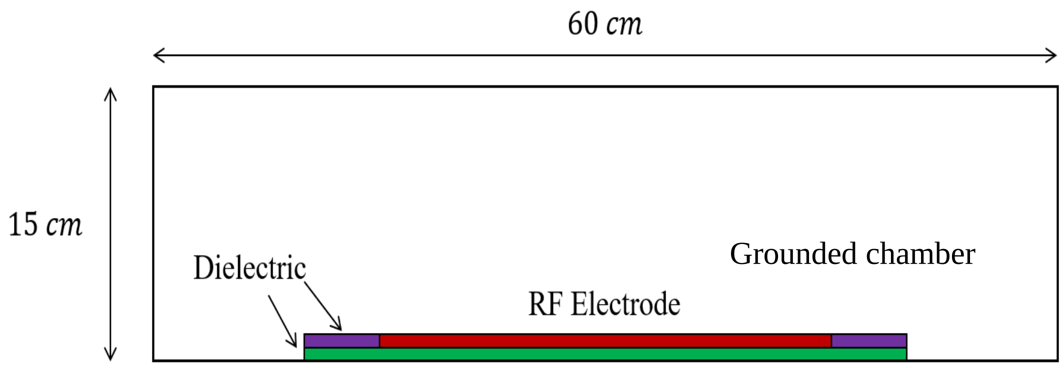
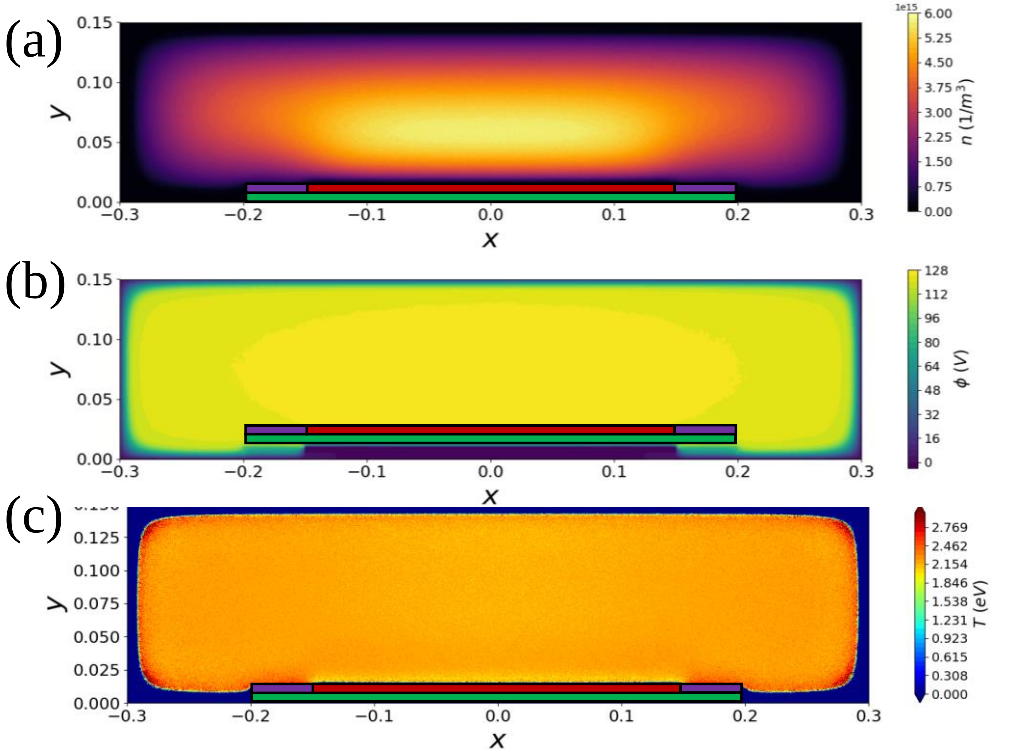
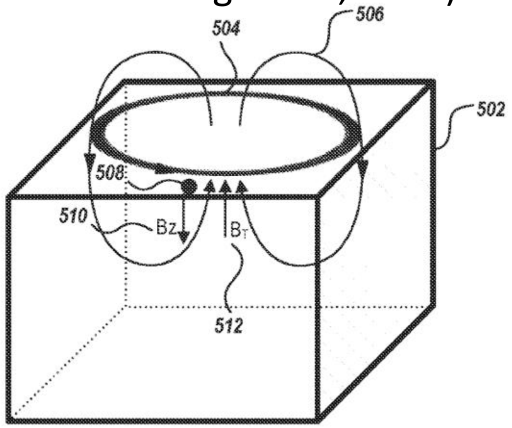


Fig. (a) Ion density, (b) plasma potential and (c) electron temperature at steady state

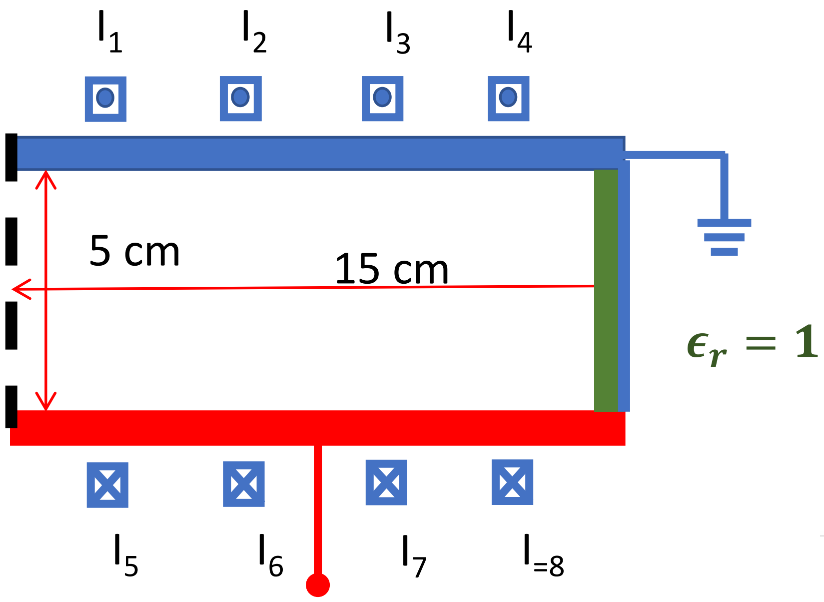


Weakly magnetized CCP in cylindrical

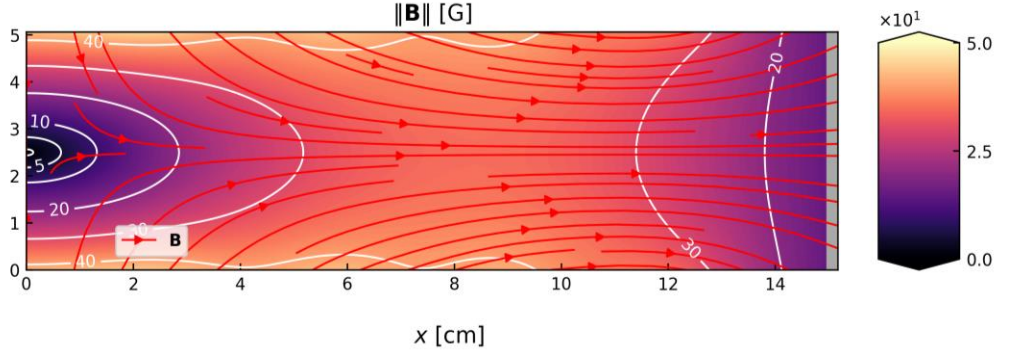
US Patent Application for PLASMA DISCHARGE UNIFORMITY CONTROL USING MAGNETIC FIELDS Patent Application (Application #20230260768 issued August 17, 2023)



CASE C (8 wires)

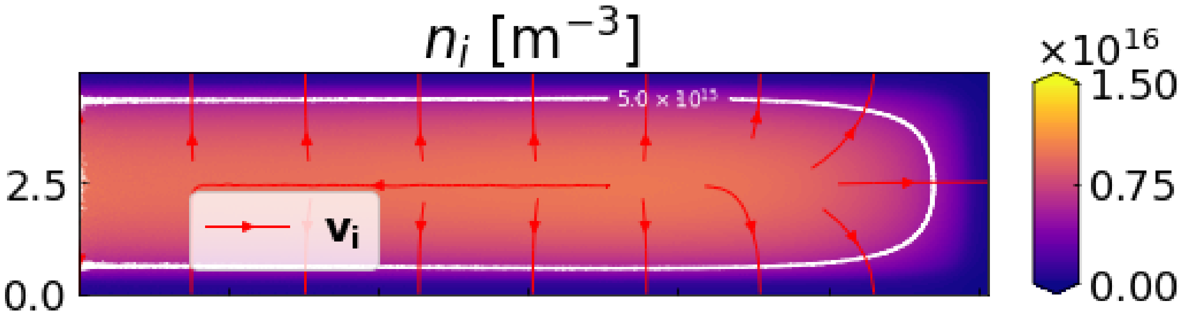


V=V_1*sin(2πf_1t)

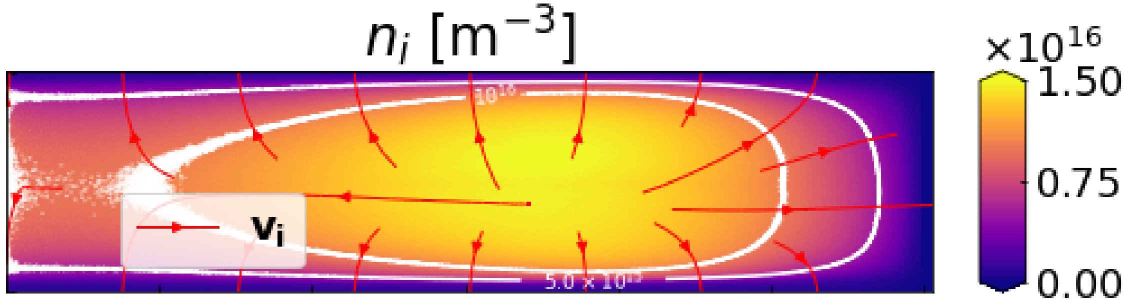


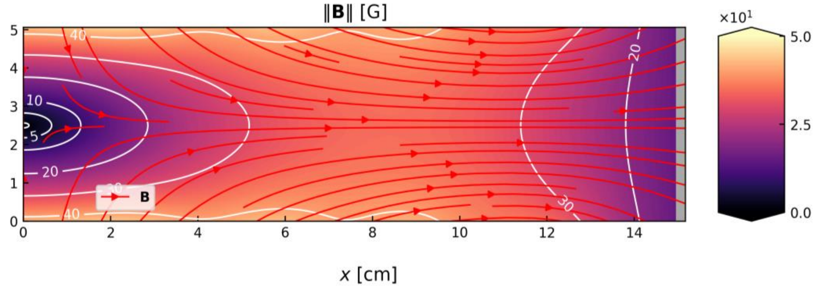
Weakly magnetized CCP

Case A: no B field



Case C: eight loops



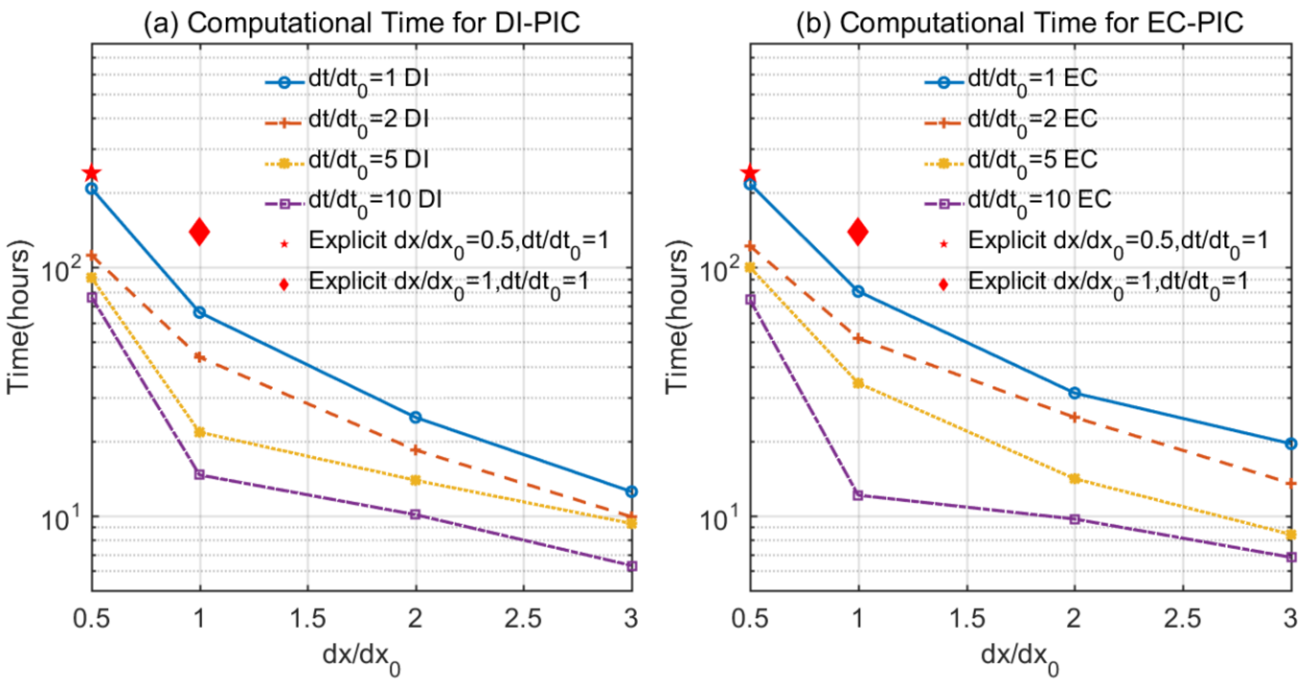


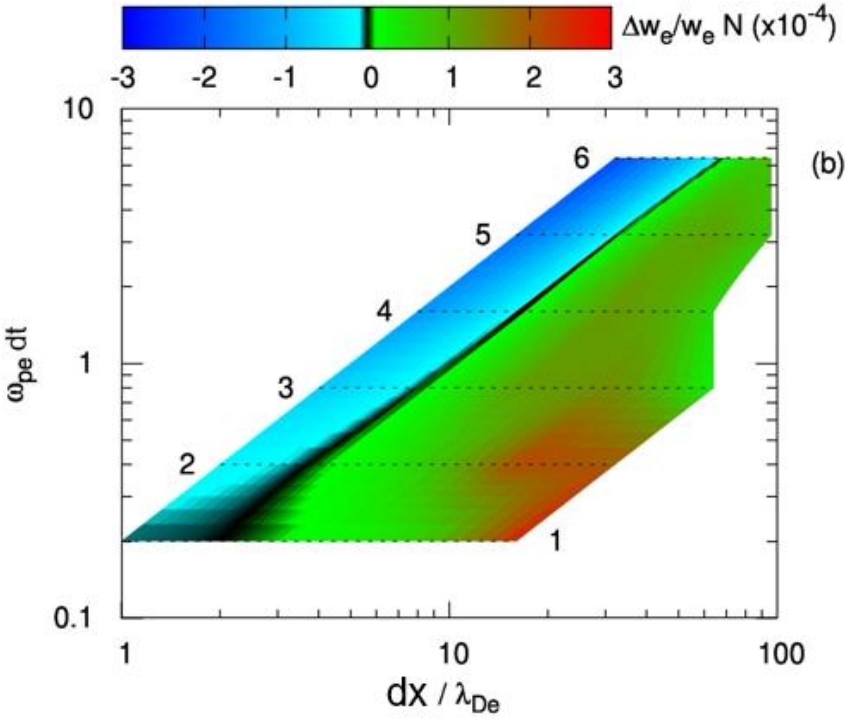
Plasma confinement where magnetic field is parallel to the walls

Reducing the number of cells and time steps

Modeling a CCP system with alternative schemes:
Direct Implicit and Energy Conserving

Can obtain a significant speed up





Numerical heating or cooling in DI can be mitigated

[1] H. Sun, et al "Direct implicit and explicit energy-conserving particle-in-cell methods for modeling of capacitively coupled plasma devices," Physics of Plasmas **30**(10), 103509 (2023).

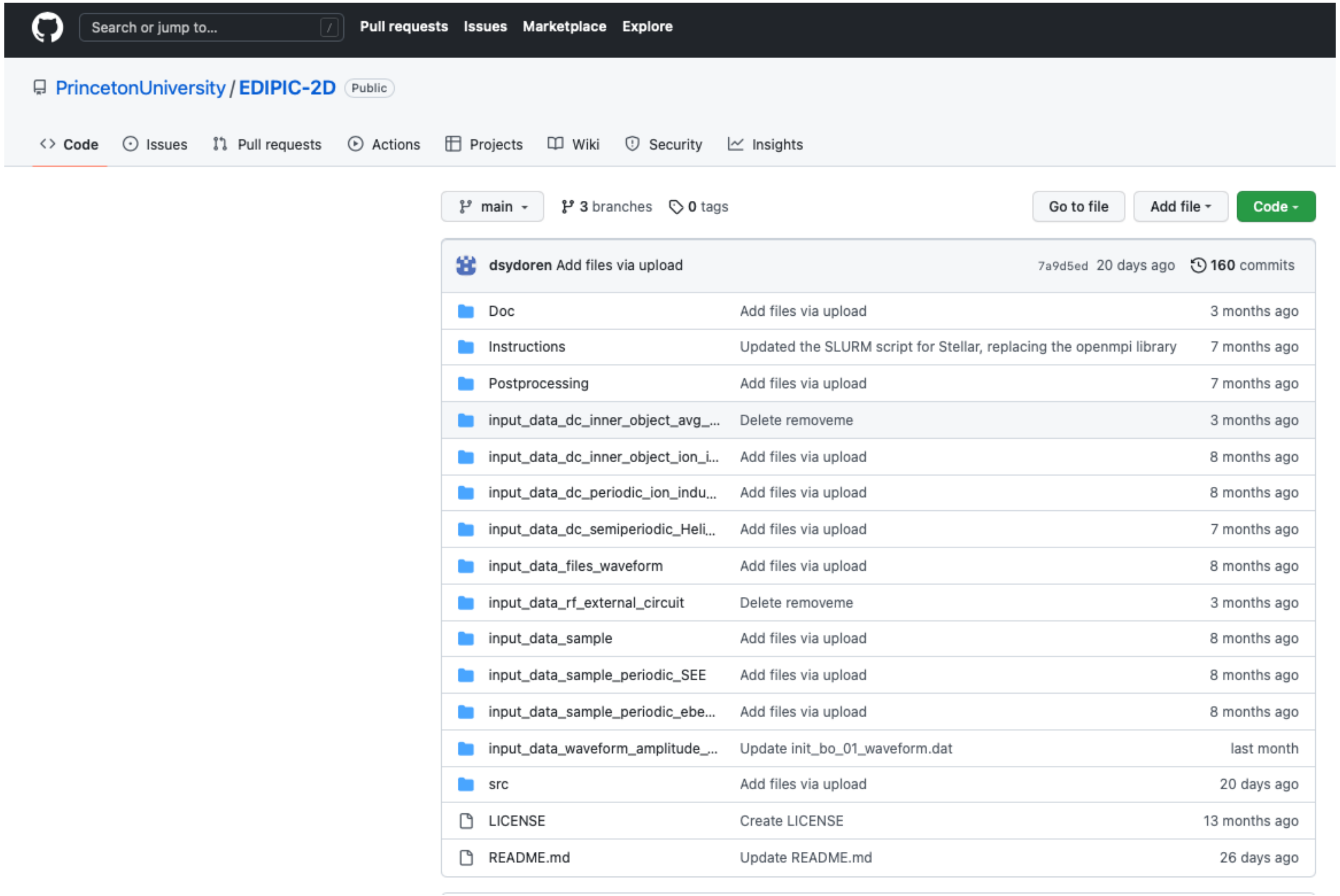
Context and Motivation

INDUSTRY
- Industry invests $billions in large, complex machines for chip manufacturing (etching and deposition)
- Machines have limited diagnostics
- Fundamental research “takes too long” and is too expensive (prefer trial-and-error)
- However, industry recognizes the benefits that theoretical and computational research can bring

MODELING NEEDS
- Fully **kinetic treatment** of low temperature plasmas (ICP, CCP, ECR, electron beam generated plasmas, hollow cathodes, dc and rf magnetrons, etc.)
- Complete reaction pathway of chemistry in the plasma and at the interface with surface
- Any insights on the plasma and chemical processes at play can give them a **huge advantage** over competition

EDIPIC: How to use?

Open source: public repository https://github.com/PrincetonUniversity/EDIPIC-2D



PrincetonUniversity / EDIPIC-2D

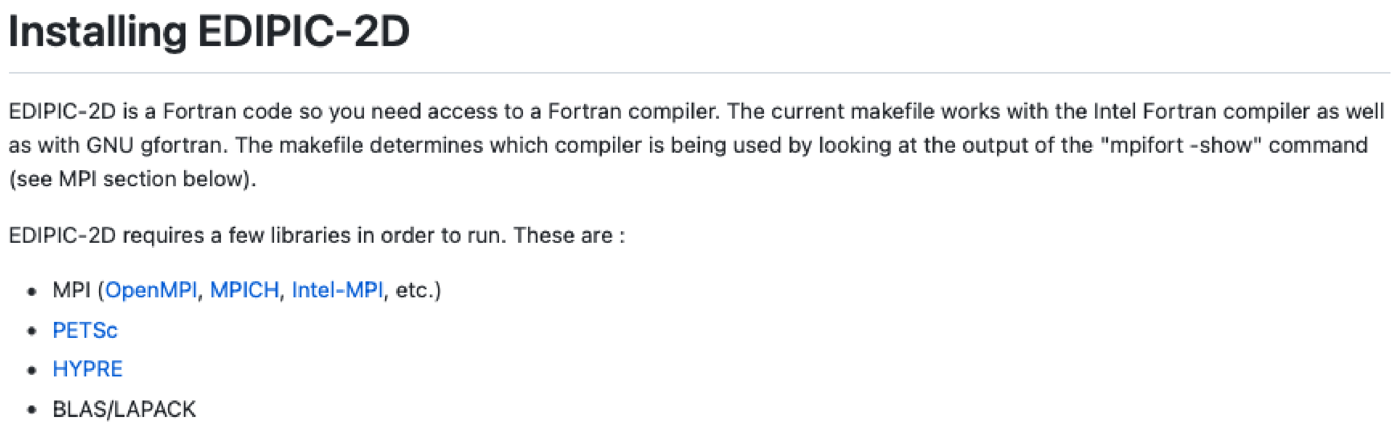
dsydoren Add files via upload 7a9d5ed 20 days ago 160 commits

Doc	Add files via upload	3 months ago
Instructions	Updated the SLURM script for Stellar, replacing the openmpi library	7 months ago
Postprocessing	Add files via upload	7 months ago
input_data_dc_inner_object_avg_...	Delete removeme	3 months ago
input_data_dc_inner_object_ion_i...	Add files via upload	8 months ago
input_data_dc_periodic_ion_indu...	Add files via upload	8 months ago
input_data_dc_semiperiodic_Heli...	Add files via upload	7 months ago
input_data_files_waveform	Add files via upload	8 months ago
input_data_rf_external_circuit	Delete removeme	3 months ago
input_data_sample	Add files via upload	8 months ago
input_data_sample_periodic_SEE	Add files via upload	8 months ago
input_data_sample_periodic_ebe...	Add files via upload	8 months ago
input_data_waveform_amplitude_...	Update init_bo_01_waveform.dat	last month
src	Add files via upload	20 days ago
LICENSE	Create LICENSE	13 months ago
README.md	Update README.md	26 days ago

EDIPIC: How to use?

Documentation:

- How to install on Stellar (or any clusters): https://github.com/PrincetonUniversity/EDIPIC-2D/blob/main/Instructions/installing_edipic2d.md



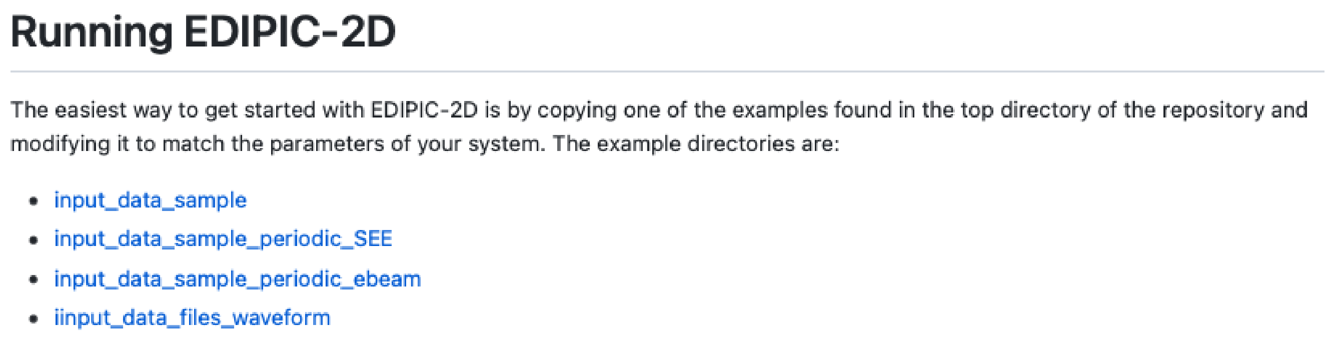
Installing EDIPIC-2D

EDIPIC-2D is a Fortran code so you need access to a Fortran compiler. The current makefile works with the Intel Fortran compiler as well as with GNU gfortran. The makefile determines which compiler is being used by looking at the output of the "mpifort -show" command (see MPI section below).

EDIPIC-2D requires a few libraries in order to run. These are :

- MPI (OpenMPI, MPICH, Intel-MPI, etc.)
- PETSc
- HYPRE
- BLAS/LAPACK

- How to run on Stellar (or any clusters) from templates: https://github.com/PrincetonUniversity/EDIPIC-2D/blob/main/Instructions/running_edipic2d.md



Running EDIPIC-2D

The easiest way to get started with EDIPIC-2D is by copying one of the examples found in the top directory of the repository and modifying it to match the parameters of your system. The example directories are:

- input_data_sample
- input_data_sample_periodic_SEE
- input_data_sample_periodic_ebeam
- iinput_data_files_waveform

EDIPIC: How to use?

Documentation:

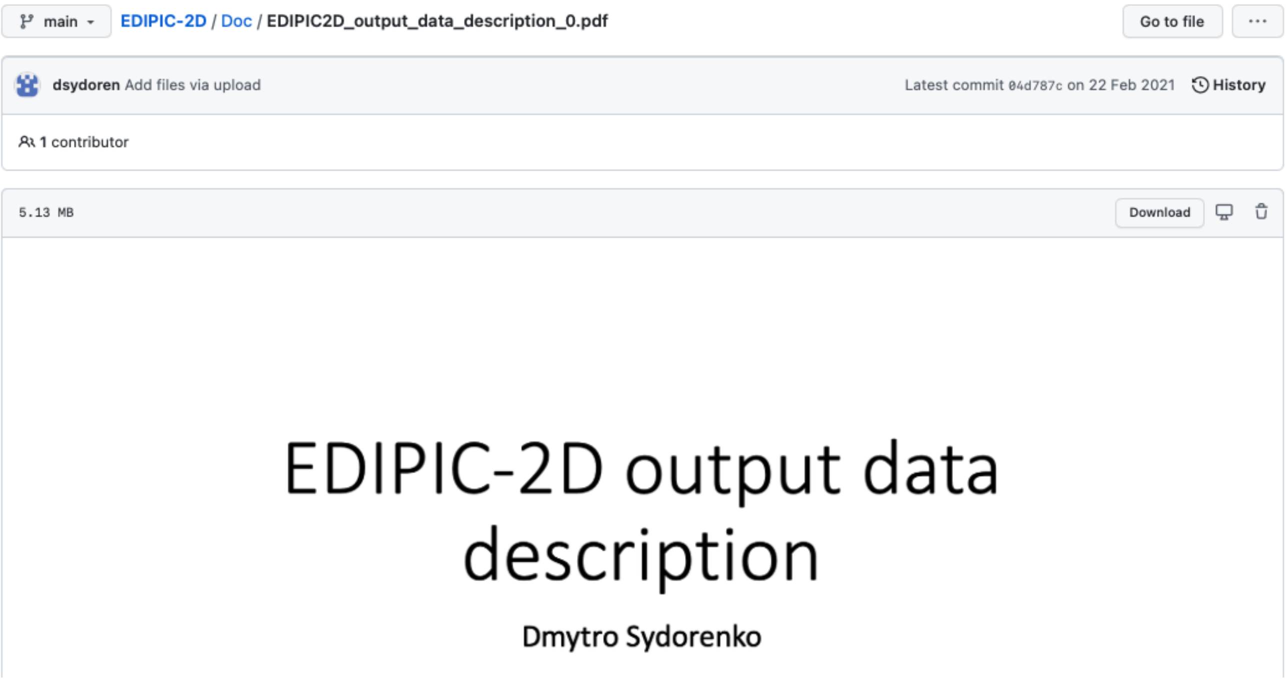
- How to post process data:
  - Via gnuplot
  - Via python scripts

https://github.com/PrincetonUniversity/EDIPIC-2D/blob/main/Doc/EDIPIC2D_output_data_description_0.pdf

- Code overview and input file description:

https://github.com/PrincetonUniversity/EDIPIC-2D/tree/main/Doc

- And we can help!



EDIPIC-2D / Doc / EDIPIC2D_output_data_description_0.pdf

dsydoren Add files via upload

Latest commit 04d787c on 22 Feb 2021

1 contributor

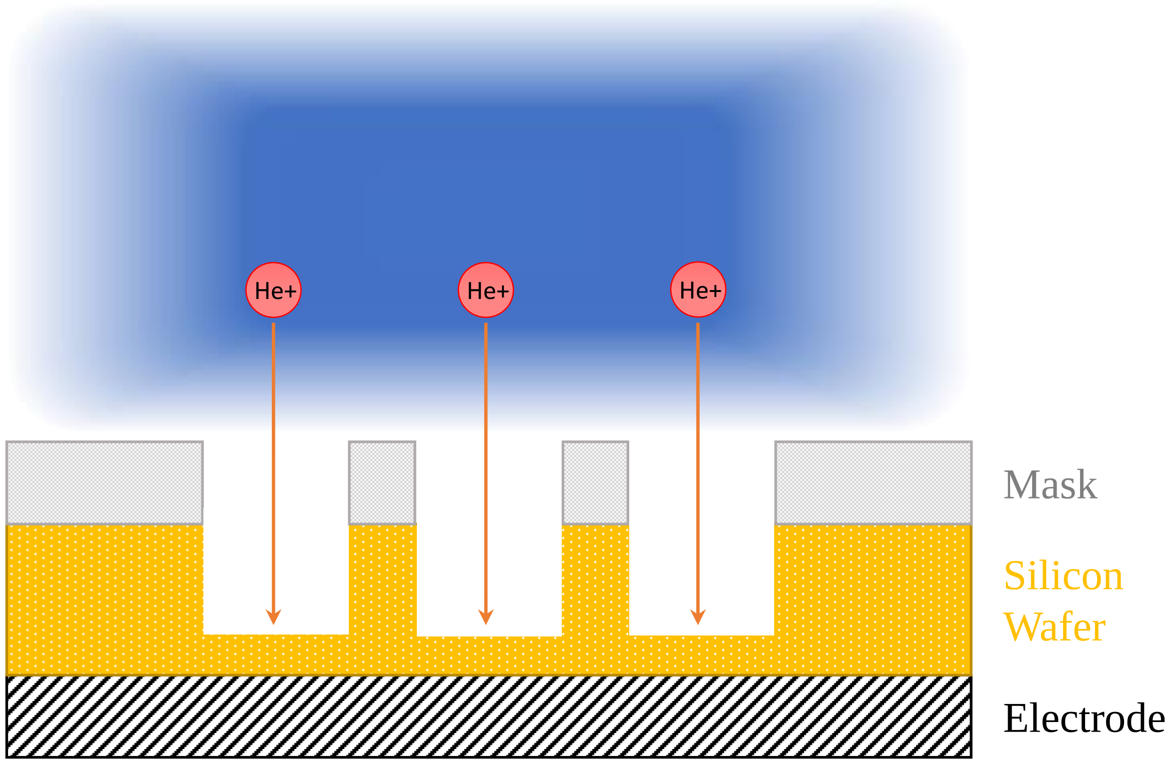
5.13 MB

EDIPIC-2D output data description

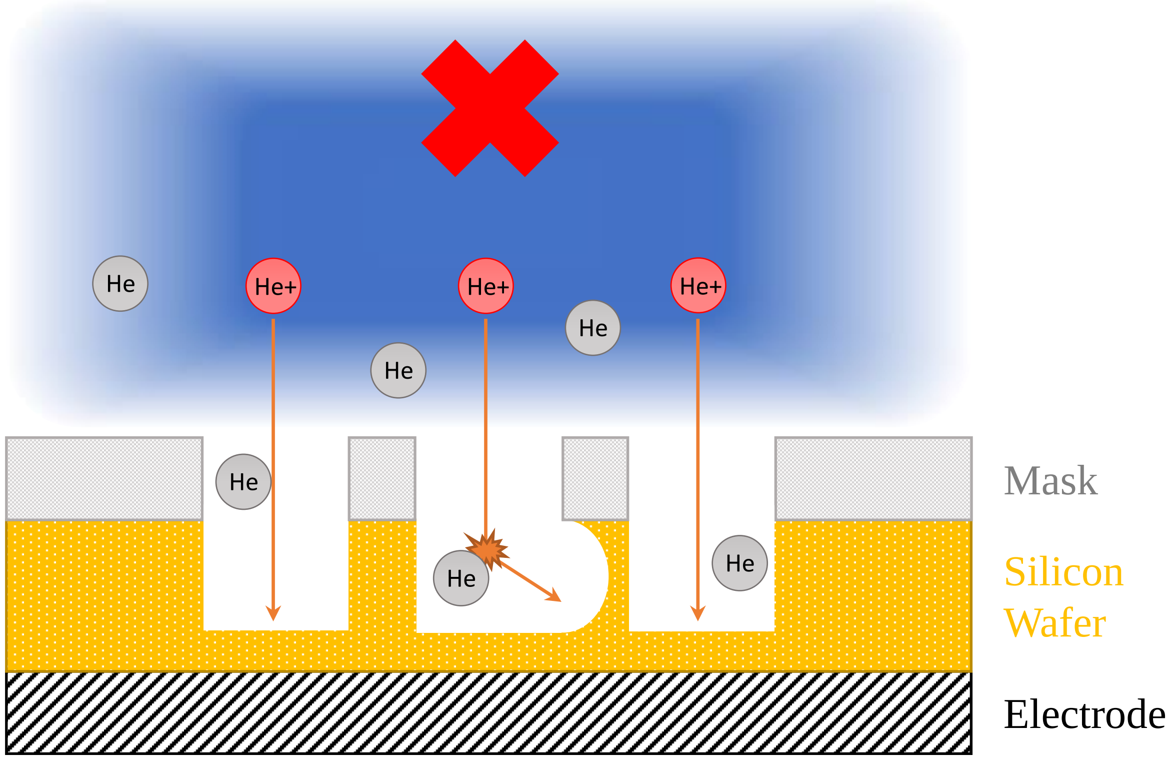
Dmytro Sydorenko

Low-pressure plasma modelling challenges

A low-pressure plasma is essential to maintain ion etch *anisotropy*



At higher pressures, the ions may collide with particles on their way to the surface deflecting their velocity vector



Low-pressure plasma modelling challenges

Often in gas or plasma simulations we rely on a **fluid** treatment

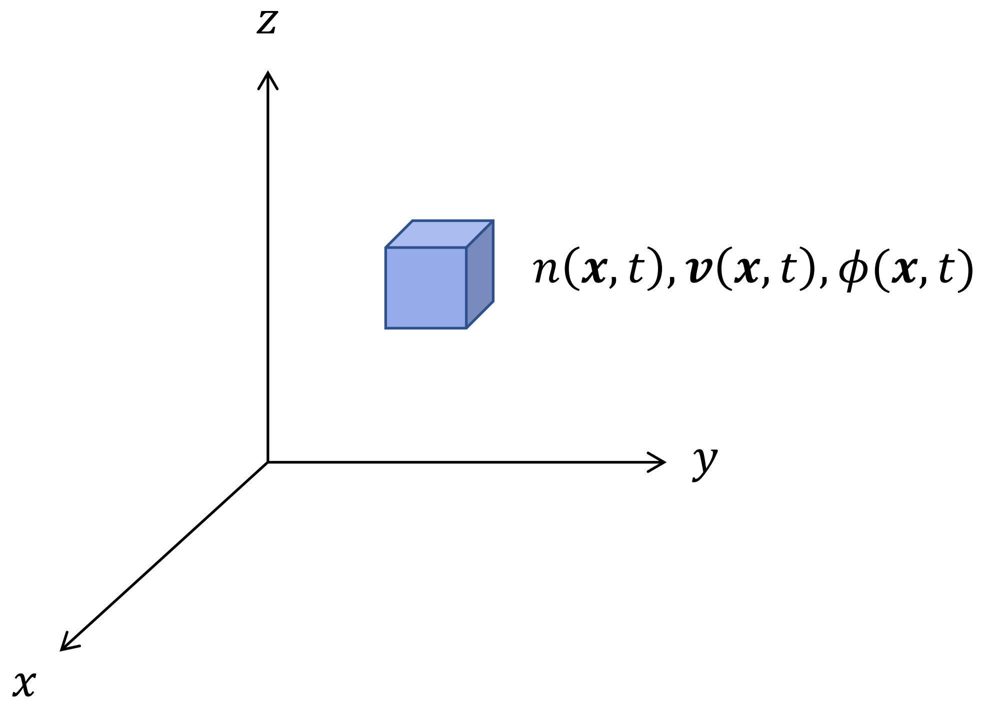
$n(\boldsymbol{x}, t)$ – Number density

$\boldsymbol{v}(\boldsymbol{x}, t)$ – Velocity vector

And if the plasma is electrostatic we can solve for:

$\phi(\boldsymbol{x}, t)$ – Electric potential

$\boldsymbol{x} = (x, y, z)$

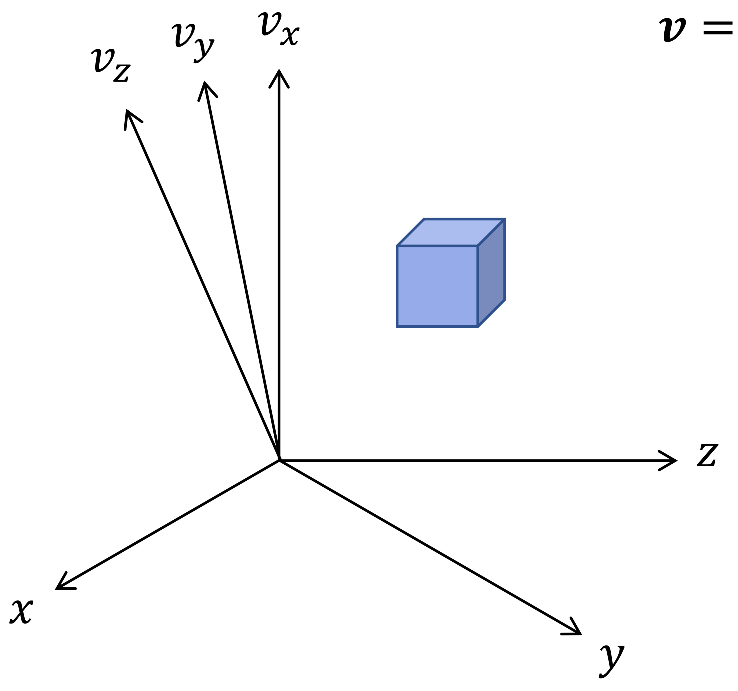


Low-pressure plasma modelling challenges

However, we are considering a *low-pressure* system, where our gas/plasma is weakly collisional

In this case we cannot assume that our plasma has a Maxwellian velocity distribution.

The fluid approximation breaks down and we must use a six-dimensional ***kinetic*** treatment



$\boldsymbol{x} = (x, y, z)$
$\boldsymbol{v} = (v_x, v_y, v_z)$

Low-pressure plasma modelling challenges

Kinetic plasma equations:

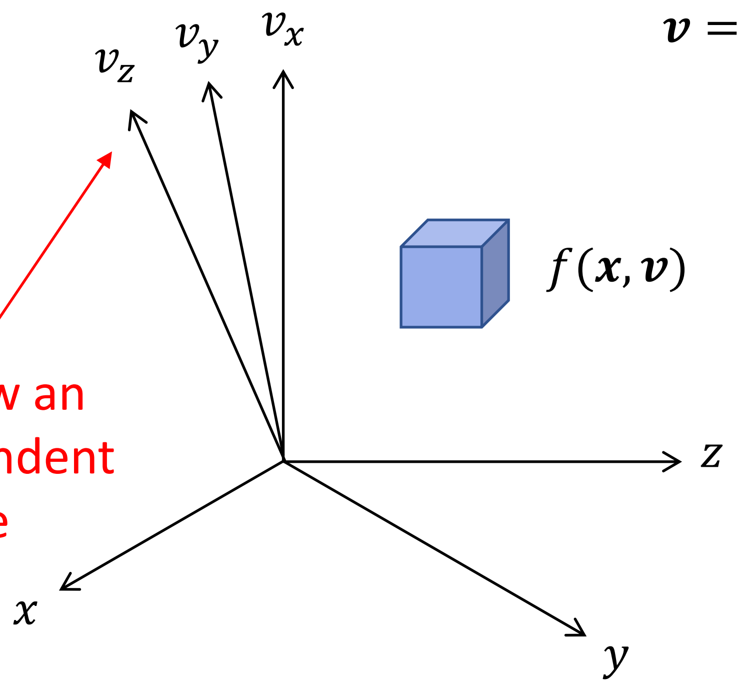
$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} - \frac{q}{m}\frac{\partial \phi}{\partial \boldsymbol{x}} \cdot \frac{\partial f}{\partial \boldsymbol{v}} = 0$$

With the Poisson equation:

$$\epsilon_0 \frac{\partial^2 \phi}{\partial \boldsymbol{x}^2} = -q \int f d\boldsymbol{v}$$

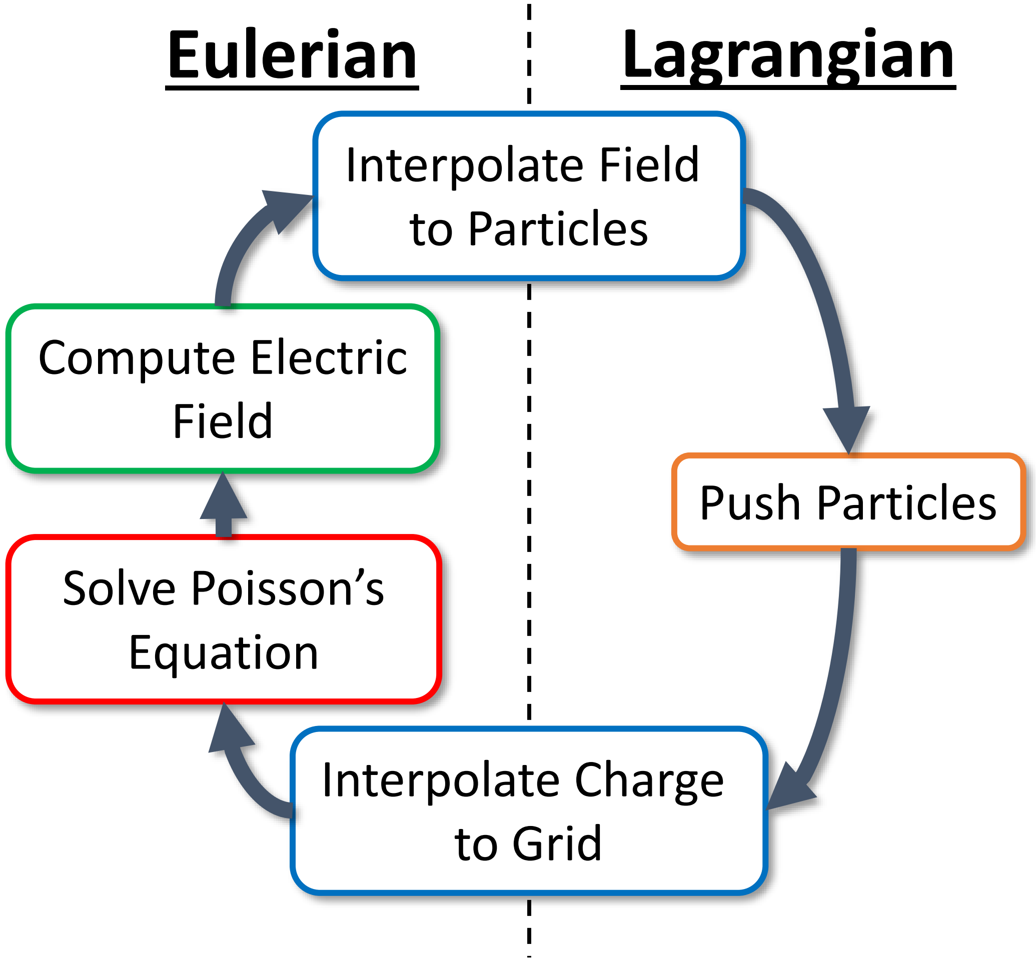
$\boldsymbol{v}$ is now an independent variable

$\boldsymbol{r} = (x, y, z)$
$\boldsymbol{v} = (v_x, v_y, v_z)$



Low-pressure plasma modelling challenges

Solve kinetic equation via Particle-In-Cell simulations



Eulerian

Lagrangian

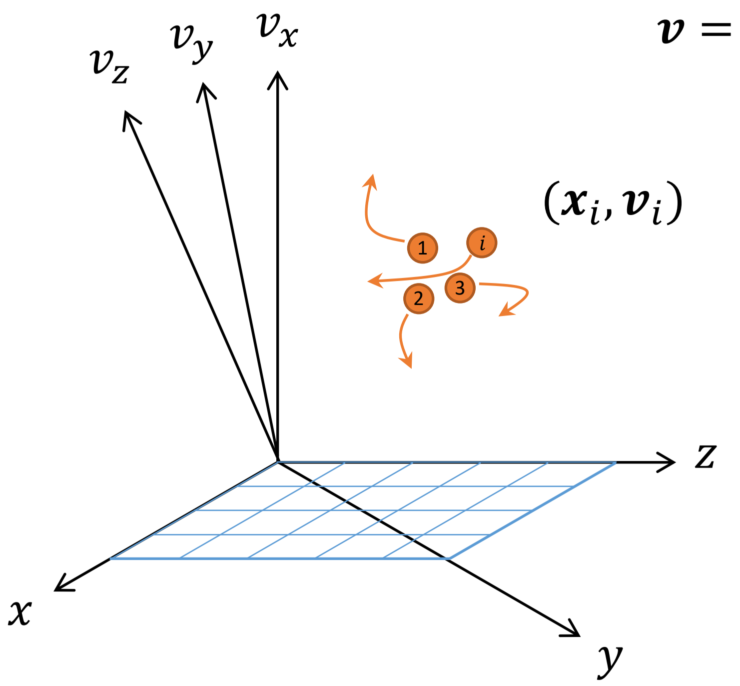
Interpolate Field to Particles

Push Particles

Interpolate Charge to Grid

Solve Poisson's Equation

Compute Electric Field

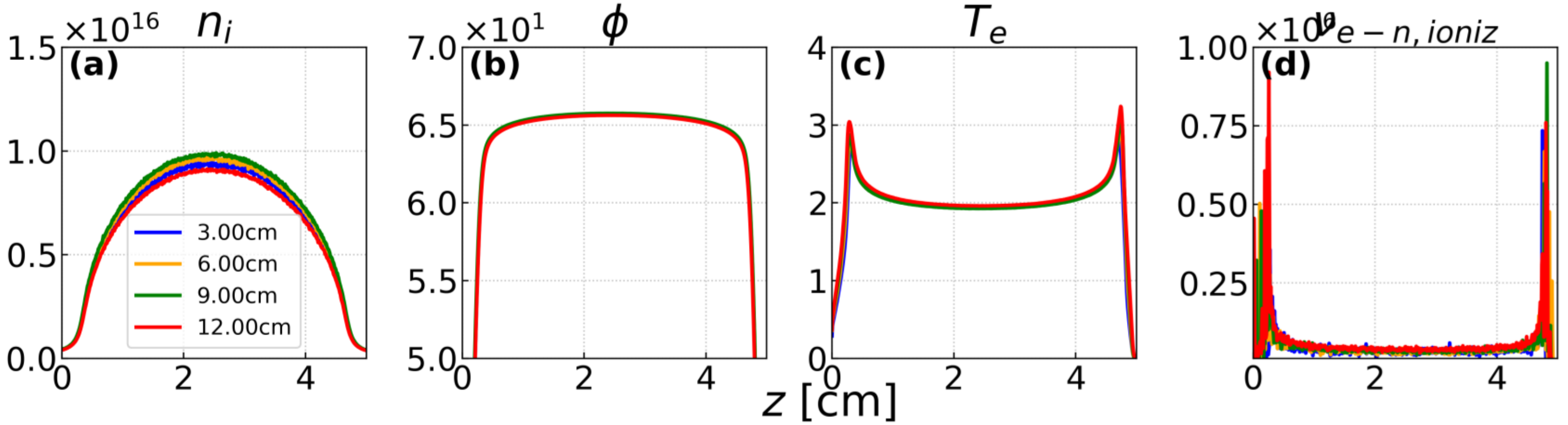


$\boldsymbol{x} = (x, y, z)$

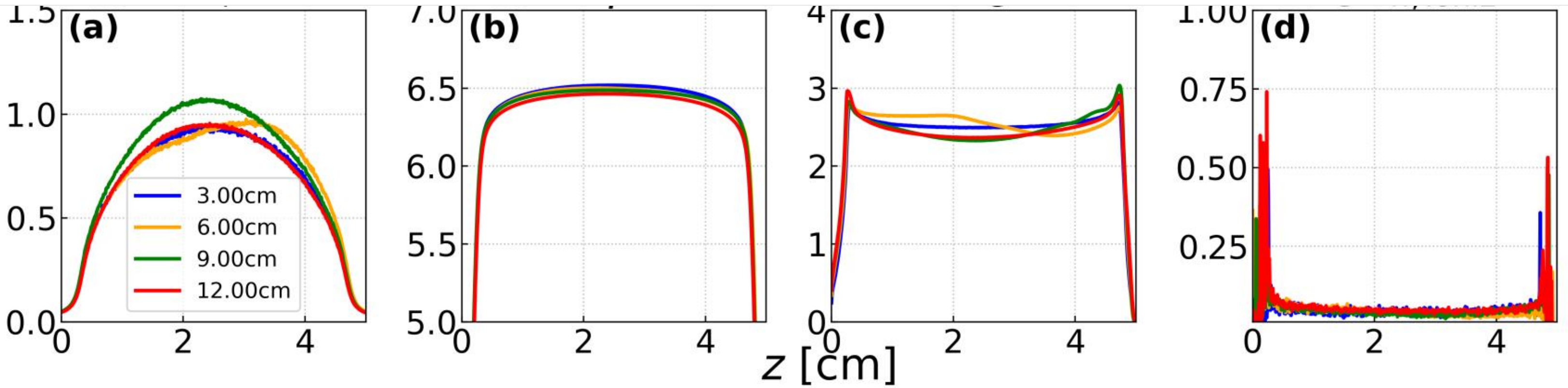
$\boldsymbol{v} = (v_x, v_y, v_z)$

1D cuts at radial locations

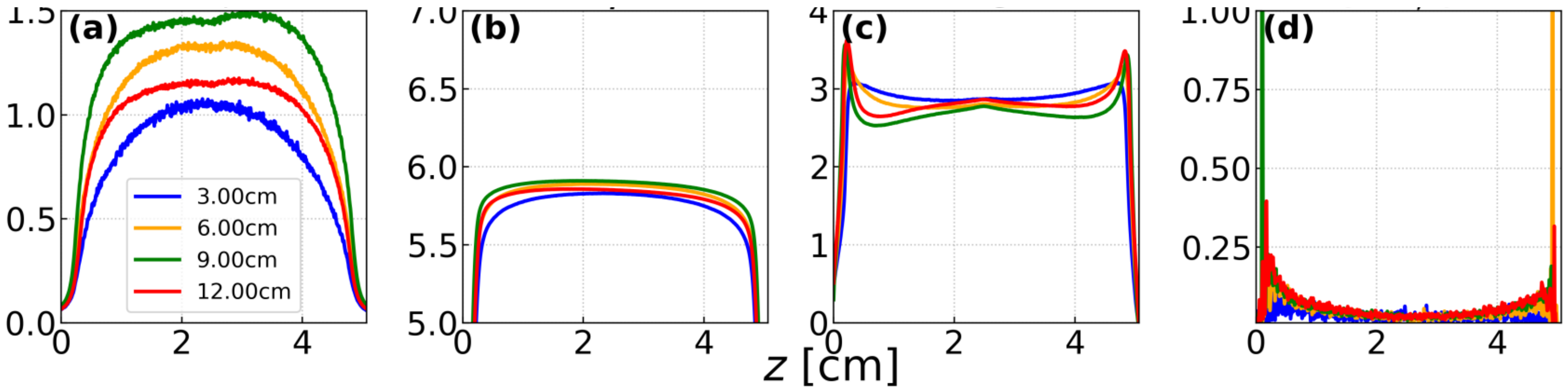
Case A: no B field



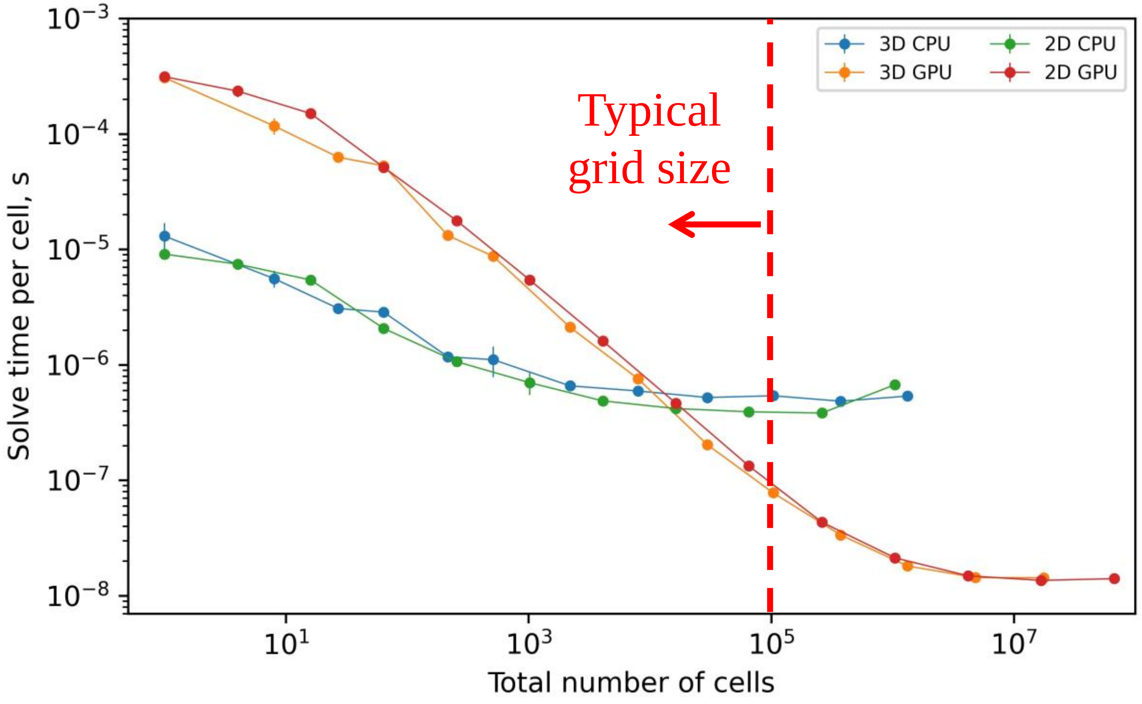
Case B: one loop



Case C: eight loops



Accelerating LTP-PIC with *OpenACC*

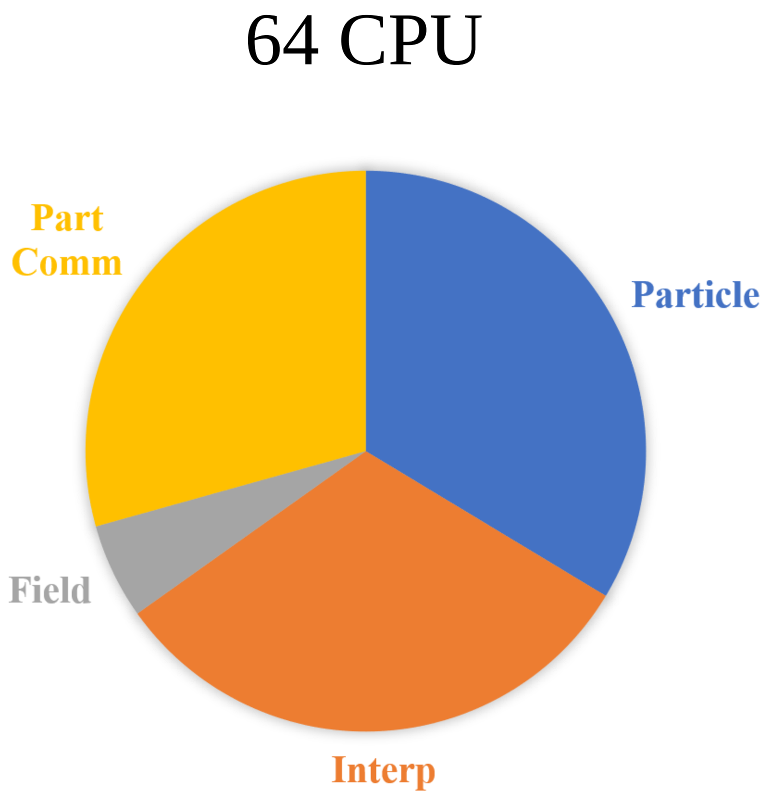


Assume, on a single GPU, ~10 GB per plasma species:

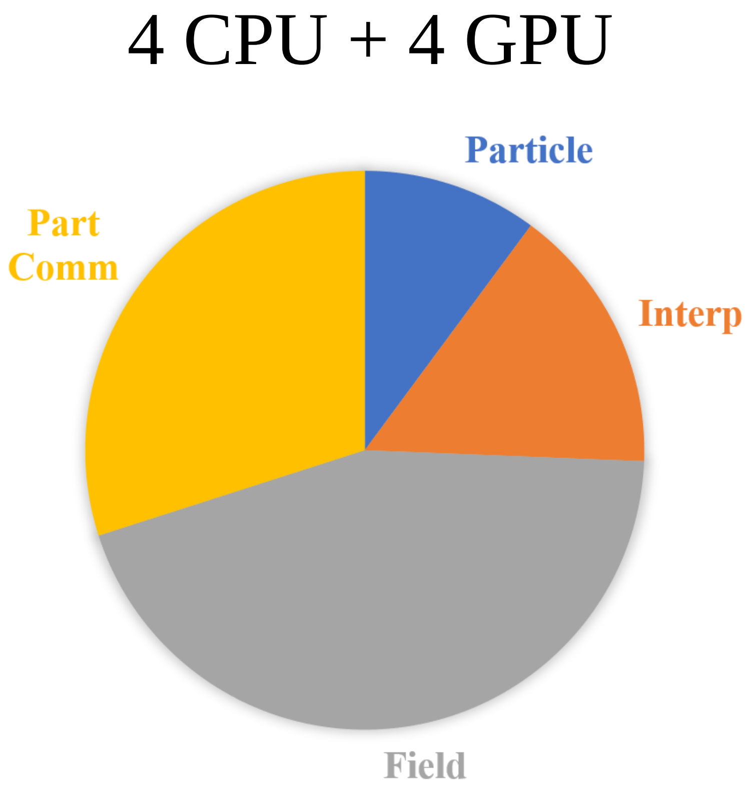
- This allows us to model around 10^8 particles, per-species, per-GPU
- Corresponding to around 10^5 cells per-GPU

Such a grid is not big enough to take full advantage of the GPU

Accelerating LTP-PIC with *OpenACC*



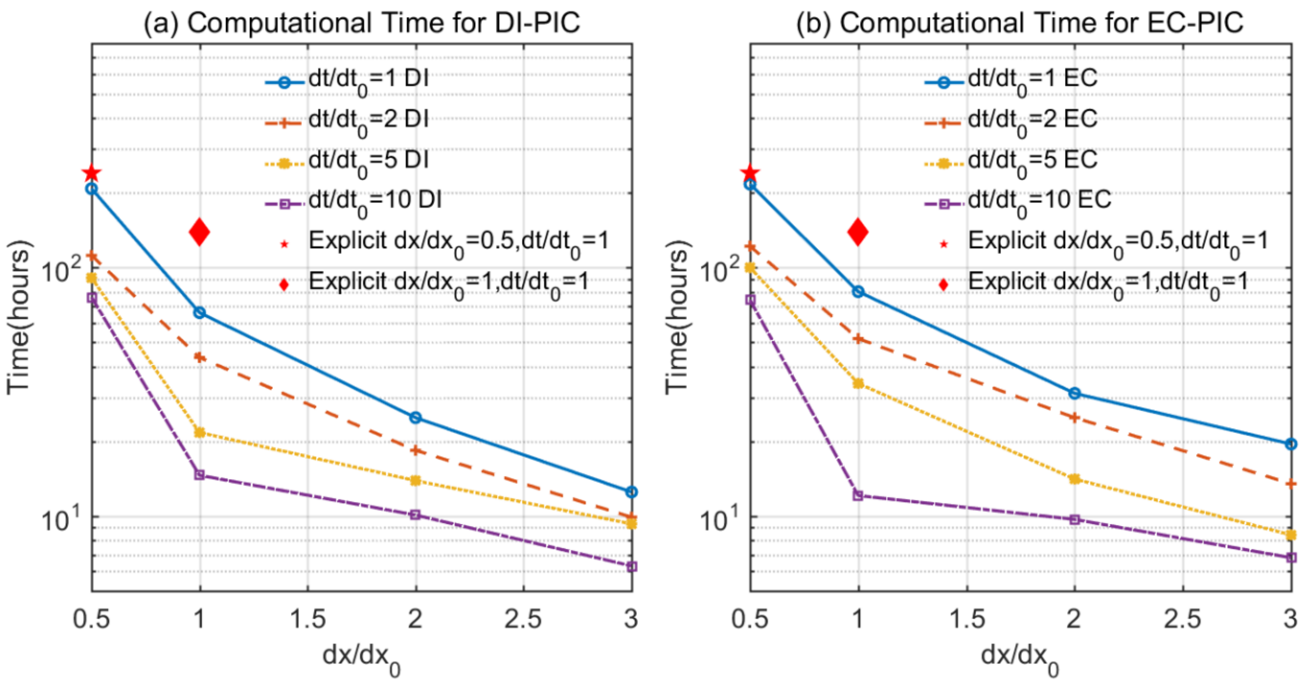
<u>2D simulations</u>
modelling $8{,}192^2$
cells with 1,000
particles-per-cell



Reducing the number of cells and time steps

Modeling a CCP system with alternative schemes [1]:

Direct Implicit and Energy Conserving



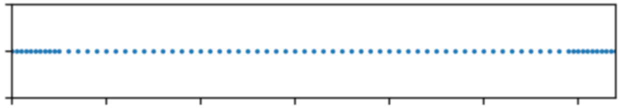
Can obtain a significant **speed up x10**
Simulations were verified with a classic momentum conserving explicit PIC schemes

[1] H. Sun, et al "Direct implicit and explicit energy-conserving particle-in-cell methods for modeling of capacitively coupled plasma devices," Physics of Plasmas **30**(10), 103509 (2023).

Reducing the number of cells and time steps

Energy conserving test on 1D CCP benchmark [1]

Non uniform grid at the sheaths

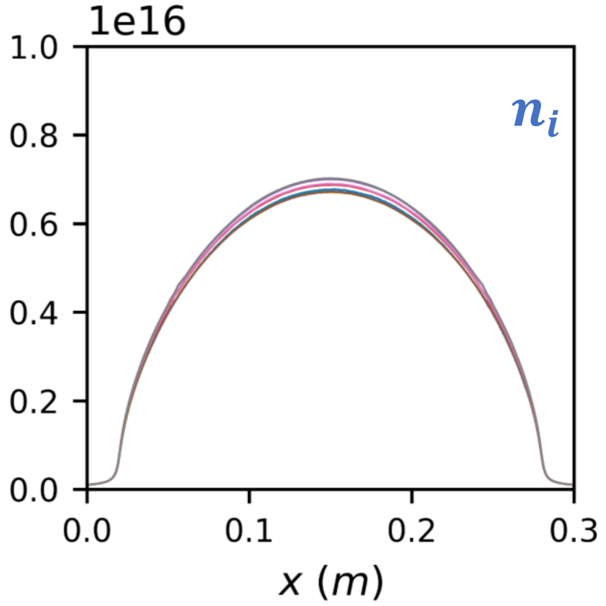


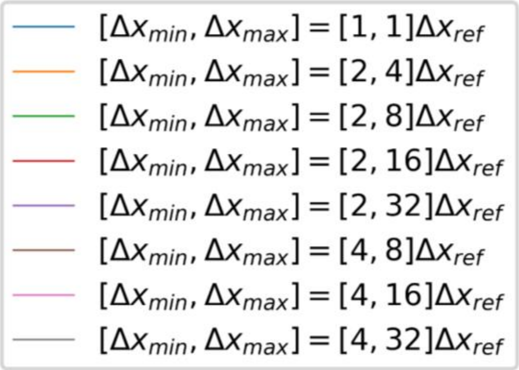
<ins>For the lowest resolution case 1-norm error of:</ins>

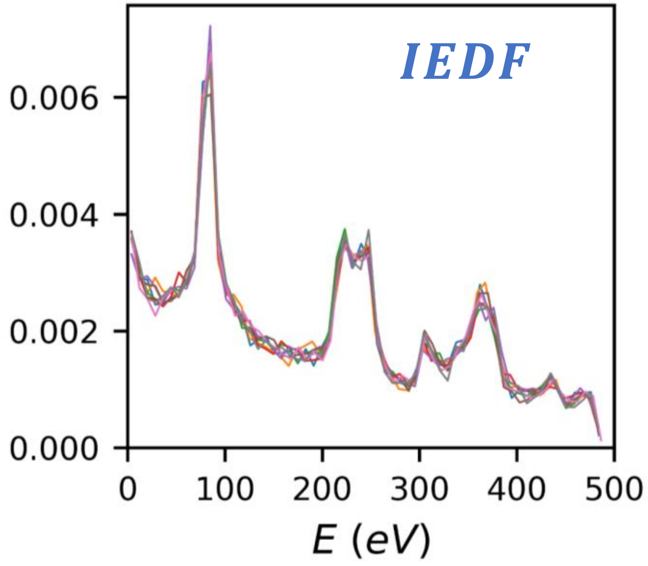
Ion density 4.3%.

Electron temp 5.1%.

This corresponds to a 10x reduction in number of cells [2].







[1] M.M. Turner, et al, "Simulation benchmarks for low-pressure plasmas: Capacitive discharges," Physics of Plasmas **20**(1), 013507 (2013).

[2] Preprint available at arXiv:2308.13092