Fourth WG4 working meeting - Large Avalanches Topical Meeting

Tuesday 11 Jun 2024, 15:00 → 18:00 Europe/Zurich

Large Avalanches and Space Charge
an introduction

P.Fonte

LIP

Disclaimer: this is not a review talk.
It's just a fast introduction + some ideas

Space-charge in parallel geometry 4 mm gap

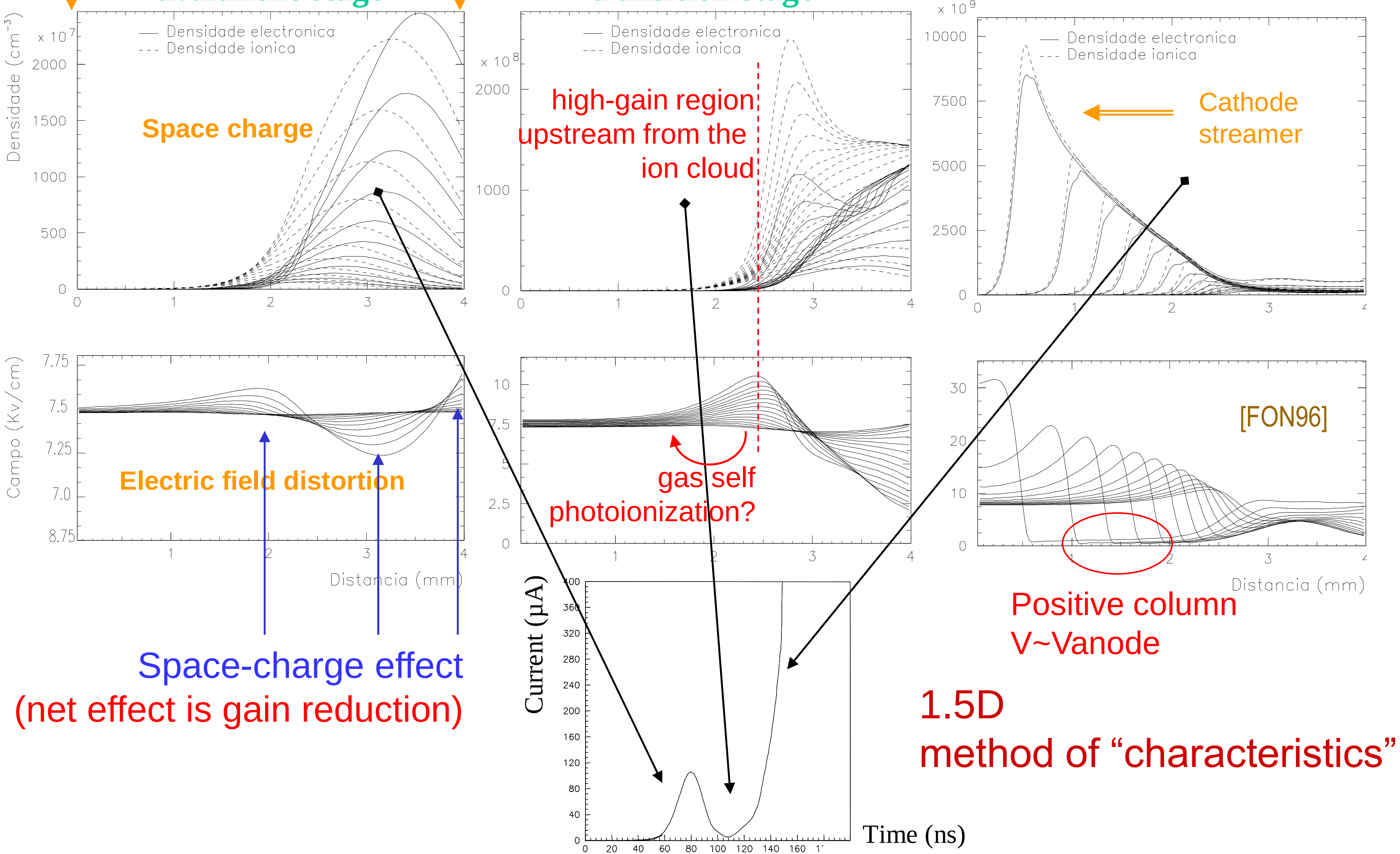
Cathode

Anode

Proportional avalanche stage

Avalanche-streamer transition stage

Streamer stage



Space charge

Electric field distortion

Space-charge effect

(net effect is gain reduction)

high-gain region upstream from the ion cloud

gas self photoionization?

Cathode streamer

[FON96]

Positive column

V~Vanode

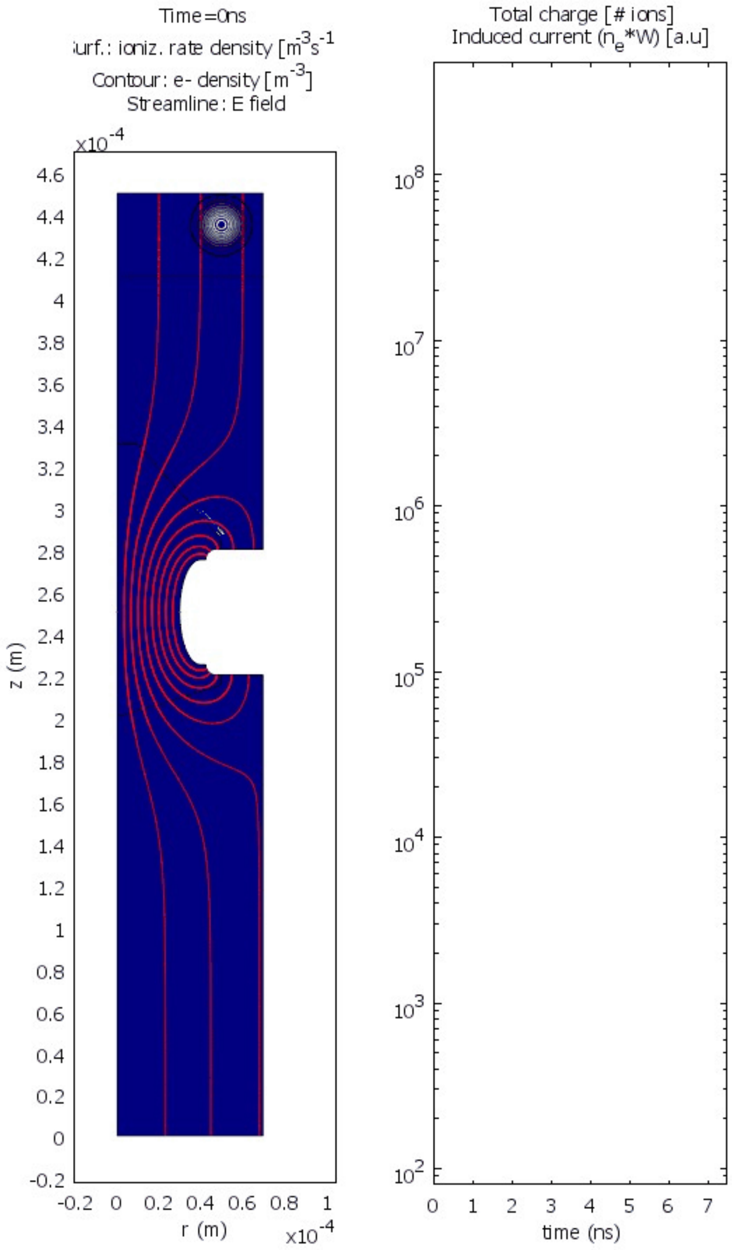
1.5D

method of “characteristics”

GEM lateral (ring) avalanche

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V

Hydrodynamic approach 2D



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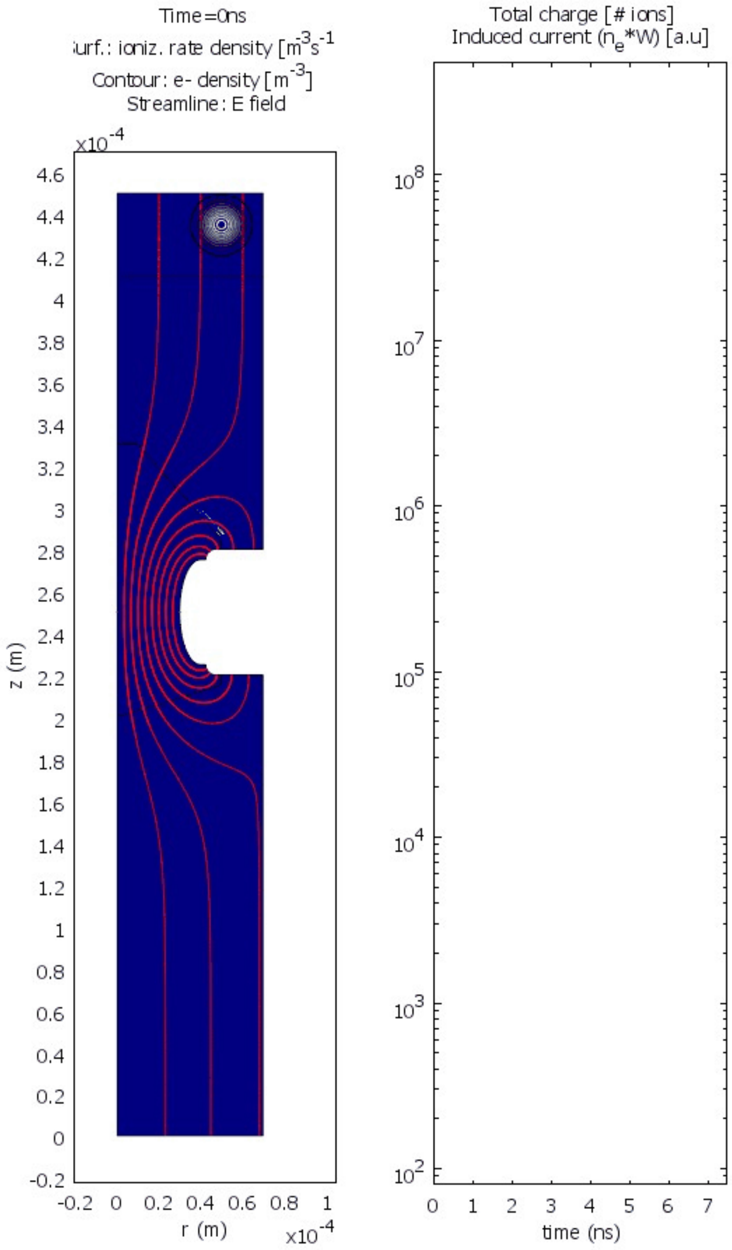


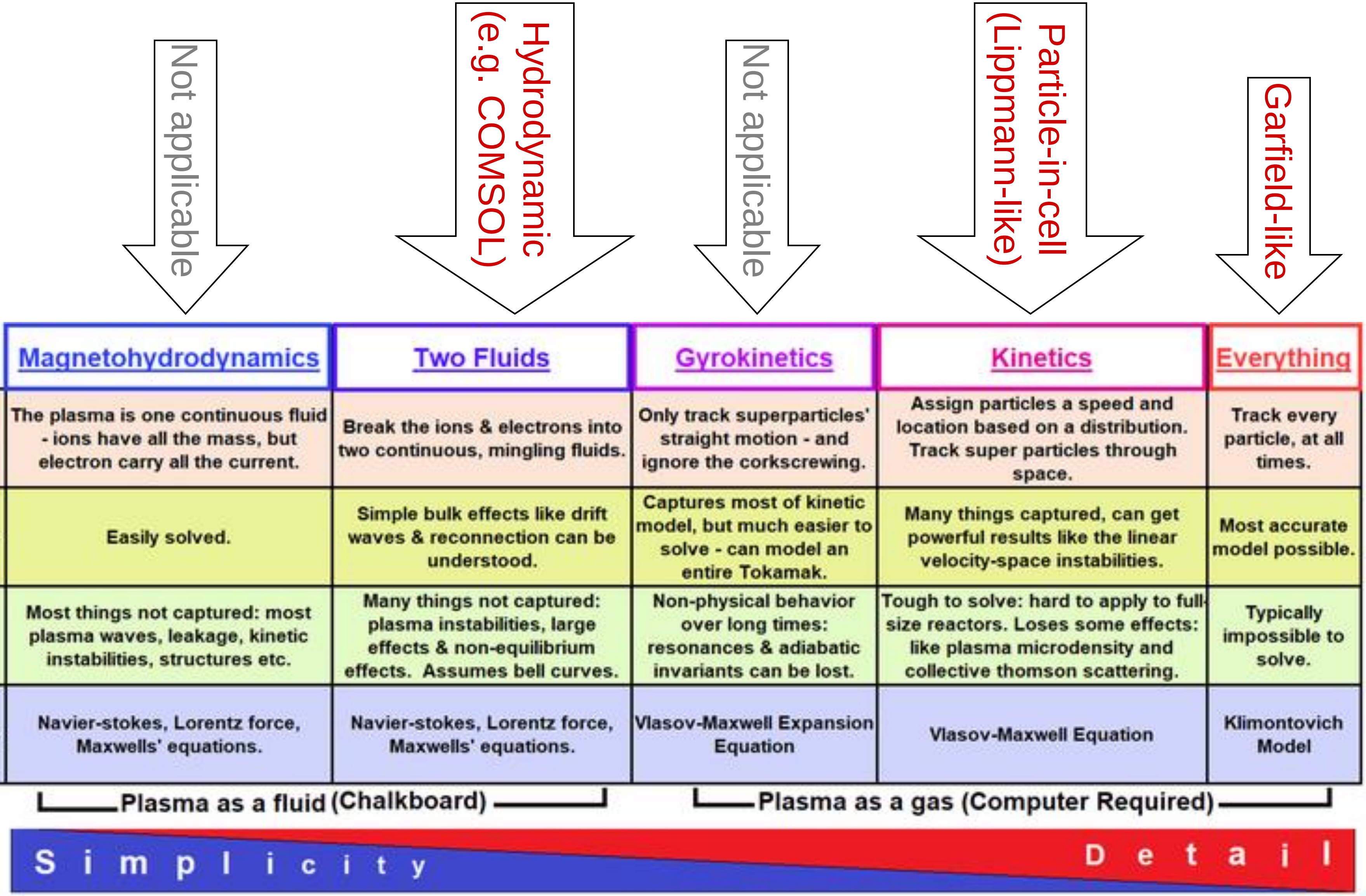
Hydrodynamic approach 2D

Similar simulations of various MPGDs can be viewed here.

https://indico.cern.ch/event/709670/contributions/3008591/

Calculation strategies

Plasma physicists have been hard at work on this for a century. Let´s see what they came up with.



Not applicable

Hydrodynamic (e.g. COMSOL)

Not applicable

Particle-in-cell (Lippmann-like)

Garfield-like

	Magnetohydrodynamics	Two Fluids	Gyrokinetics	Kinetics	Everything
Description	The plasma is one continuous fluid - ions have all the mass, but electron carry all the current.	Break the ions & electrons into two continuous, mingling fluids.	Only track superparticles' straight motion - and ignore the corkscrewing.	Assign particles a speed and location based on a distribution. Track super particles through space.	Track every particle, at all times.
Strengthens	Easily solved.	Simple bulk effects like drift waves & reconnection can be understood.	Captures most of kinetic model, but much easier to solve - can model an entire Tokamak.	Many things captured, can get powerful results like the linear velocity-space instabilities.	Most accurate model possible.
Weakness	Most things not captured: most plasma waves, leakage, kinetic instabilities, structures etc.	Many things not captured: plasma instabilities, large effects & non-equilibrium effects. Assumes bell curves.	Non-physical behavior over long times: resonances & adiabatic invariants can be lost.	Tough to solve: hard to apply to full-size reactors. Loses some effects: like plasma microdensity and collective thomson scattering.	Typically impossible to solve.
Mathematics	Navier-stokes, Lorentz force, Maxwells' equations.	Navier-stokes, Lorentz force, Maxwells' equations.	Vlasov-Maxwell Expansion Equation	Vlasov-Maxwell Equation	Klimontovich Model

Plasma as a fluid (Chalkboard)

Plasma as a gas (Computer Required)

[Wiki1]

It seems that the two-fluid approach will be faster than the others.

Hydrodynamic (for sparse avalanches, for plasmas it is way more complicated)

good reference: [DAV73]

$$\overbrace{\frac{\partial n_e(\vec{r},t)}{\partial t}+\vec{\nabla}\cdot\underbrace{\left(\underset{\textit{transport}}{\vec{W}_e n_e}-\underbrace{D_e\vec{\nabla}n_e}_{\textit{diffusion}}\right)}_{\textit{electron flow density }\vec{J}_e}}^{\textit{conservation}}=\overbrace{\underset{\textit{other sources}}{S}+\underbrace{(\alpha-\eta)\left|\vec{J}_e\right|}_{\textit{multiplication}\atop -\textit{attachment}}}^{\textit{creation}}$$

Electrons

$n(\vec{r},t)$ = charge density in space and time

$\vec{W}_e(\vec{E})$ = velocity of electrons

$\vec{E}(\vec{r},t)$ = electric field: applied + space charge

α=first Townsend coefficient

η=attachment coefficient

D_e=diffusion coefficient

$$\frac{\partial n_{i+}(\vec{r},t)}{\partial t}=S+\alpha\left|\vec{J}_e\right|$$

$$\frac{\partial n_{i-}(\vec{r},t)}{\partial t}=\eta\left|\vec{J}_e\right|$$

Ions (assuming stationary ions)

Space-charge + applied field

$$\nabla^2 V=-\frac{e}{\varepsilon_0}\left(n_{i+}-n_e-n_{i-}\right)$$

Boundary conditions

initial densities: $n_{e,i\pm}(\vec{r},0)$

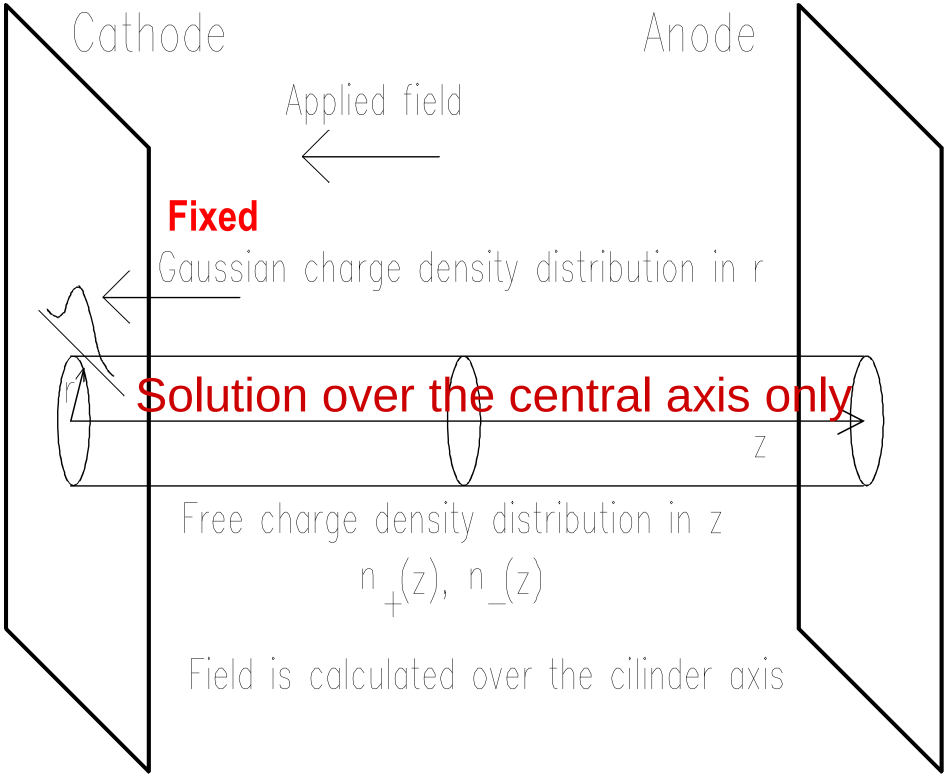
behaviour of charges at the electrodes

Electrostatic B.C.

drawback: no avalanche statistics

Some simplification from symmetry

The minimum model: “1.5D” (discs)

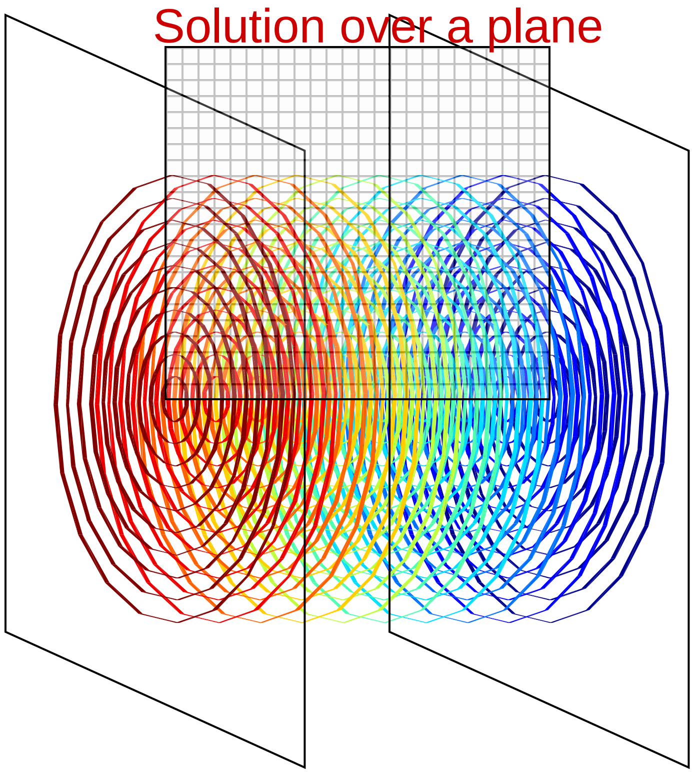


Fixed

Solution over the central axis only

Started by Davies et al. in the 60’s

Much better: “2D” (rings=axial symmetry)



Solution over a plane

Unfortunately, still artificial for many detectors.

Numerical strategies for hydrodynamic approach

Method of “characteristics”

Integrate the equations along “characteristic lines” that correspond to the path of the charges = electric field lines.

Equations become a set of uncoupled ordinary differential equations and analytical solutions exist for non-space charge regime.

For space-charge regime: small time steps and recalculate the field at each step.

Lateral diffusion difficult to incorporate.

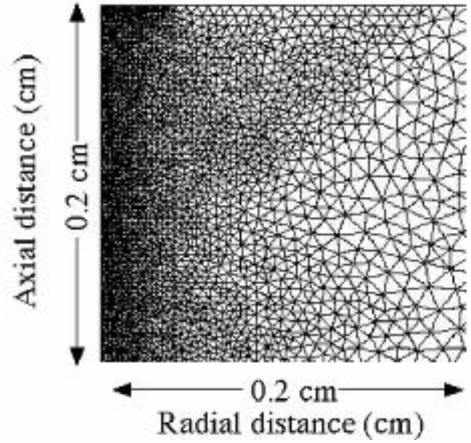
Technical difficulties with curvilinear frames of reference + interpolation between characteristics and 3D space.

Faster than FEM?

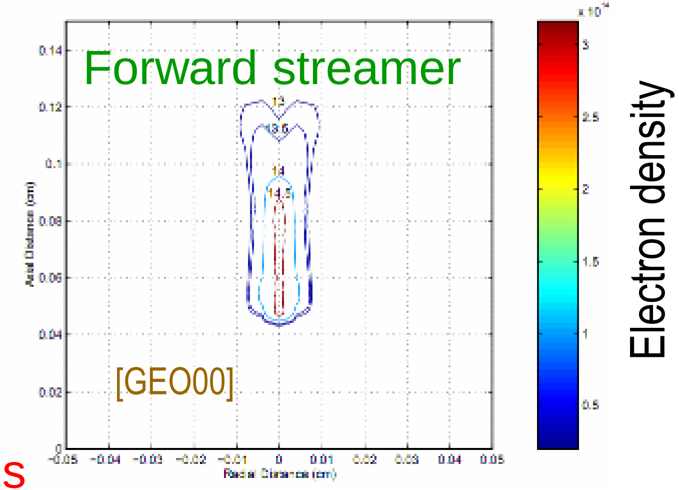
Are there other methods?
In plasma physics there are very sophisticated approaches

Finite elements method (FEM)

Solve the differential equations on the vertices of a mesh.



“2D”
axial symmetry


Forward streamer

[GEO00]

Another approach: particle-in-cell

A “mesoscopic” MonteCarlo where mini-avalanches are propagated from cell-to-cell in a mesh.

Symmetries can be also applied.

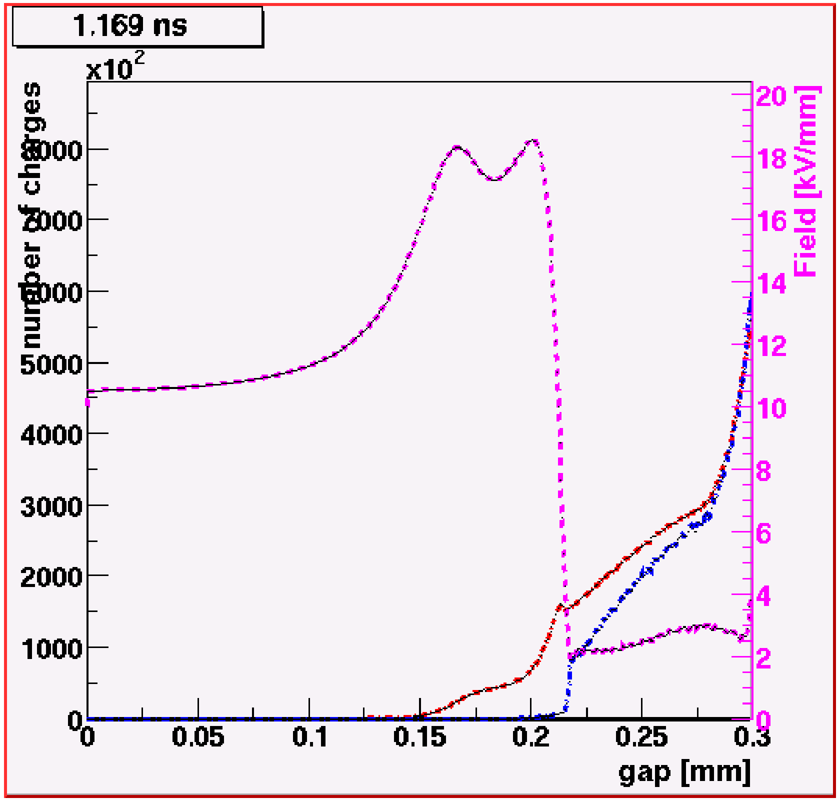
Incorporates naturally avalanche statistics.

1.5D approximation

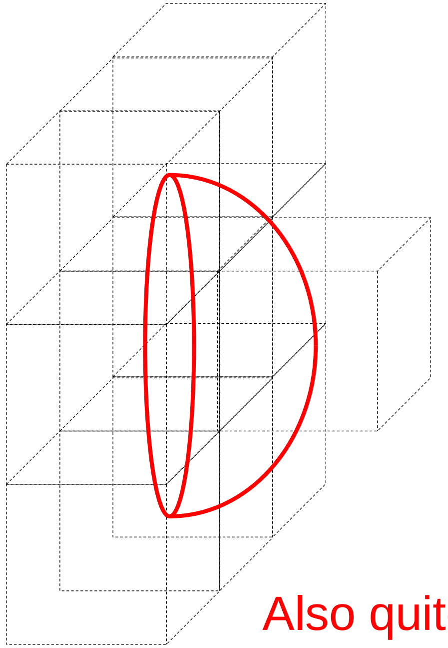
0.3mm timing RPC, 3kV

electrons, positive ions, negative ions, field

Space-charge only
no cathode streamer



[Courtesy Werner Riegler]

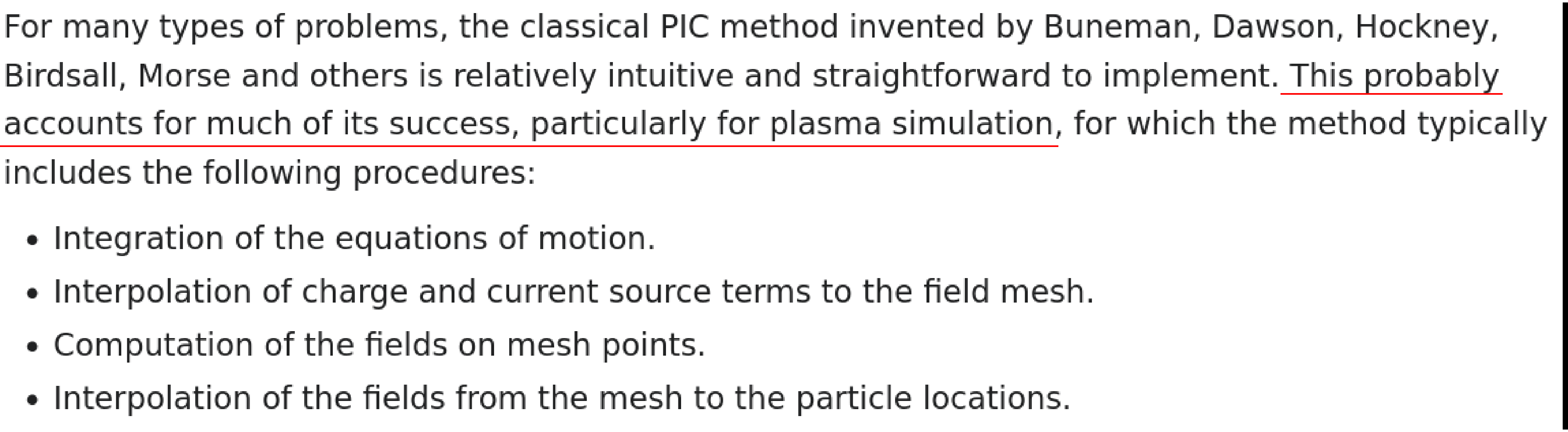


[LIP04]

Also quite formidable: enormous number of cells.
3D prohibitive

Particle-in-cell

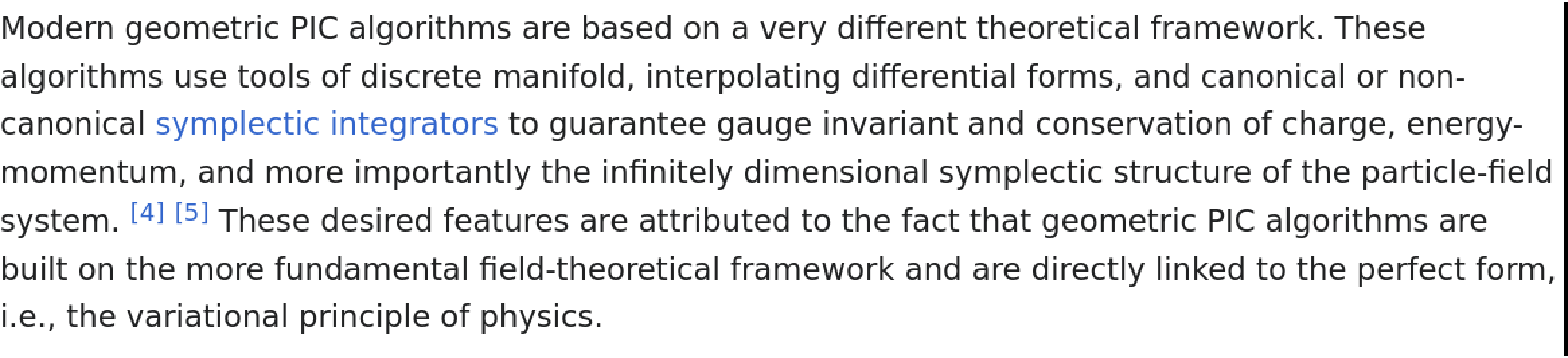
https://en.wikipedia.org/wiki/Particle-in-cell



For many types of problems, the classical PIC method invented by Buneman, Dawson, Hockney, Birdsall, Morse and others is relatively intuitive and straightforward to implement. This probably accounts for much of its success, particularly for plasma simulation, for which the method typically includes the following procedures:

- Integration of the equations of motion.
- Interpolation of charge and current source terms to the field mesh.
- Computation of the fields on mesh points.
- Interpolation of the fields from the mesh to the particle locations.

…



Modern geometric PIC algorithms are based on a very different theoretical framework. These algorithms use tools of discrete manifold, interpolating differential forms, and canonical or non-canonical symplectic integrators to guarantee gauge invariant and conservation of charge, energy-momentum, and more importantly the infinitely dimensional symplectic structure of the particle-field system. [4] [5] These desired features are attributed to the fact that geometric PIC algorithms are built on the more fundamental field-theoretical framework and are directly linked to the perfect form, i.e., the variational principle of physics.

These people seem to have a sophisticated view of the subject (and probably harder problems to solve).

Particle-in-cell

https://en.wikipedia.org/wiki/Particle-in-cell

Electromagnetic particle-in-cell computational applications [edit]

Computational application	Web site	License	Availability	Canonical Reference
SHARP	[17]	Proprietary		doi:10.3847/1538-4357/aa6d13
ALaDyn	[18]	GPLv3+	Open Repo:[19]	doi:10.5281/zenodo.49553
EPOCH	[20]	GPLv3	Open Repo:[21]	doi:10.1088/0741-3335/57/11/113001
FBPIC	[22]	3-Clause-BSD-LBNL	Open Repo:[23]	doi:10.1016/j.cpc.2016.02.007
LSP	[24]	Proprietary	Available from ATK	doi:10.1016/S0168-9002(01)00024-9
MAGIC	[25]	Proprietary	Available from ATK	doi:10.1016/0010-4655(95)00010-D
OSIRIS	[26]	GNU AGPL	Open Repo [27]	doi:10.1007/3-540-47789-6_36
PICCANTE	[28]	GPLv3+	Open Repo:[29]	doi:10.5281/zenodo.48703
PICLas	[30]	GPLv3+	Open Repo:[31]	doi:10.1016/j.crme.2014.07.005 doi:10.1063/1.5097638
PIConGPU	[32]	GPLv3+	Open Repo:[33]	doi:10.1145/2503210.2504564
SMILEI	[34]	CeCILL-B	Open Repo:[35]	doi:10.1016/j.cpc.2017.09.024
iPIC3D	[36]	Apache License 2.0	Open Repo:[37]	doi:10.1016/j.matcom.2009.08.038
The Virtual Laser Plasma Lab (VLPL)	[38]	Proprietary	Unknown	doi:10.1017/S0022377899007515
Tristan v2	[39]	3-Clause-BSD	Open source,[40] but also has a private version with QED/radiative[41] modules	doi:10.5281/zenodo.7566725 [42]
VizGrain	[43]	Proprietary	Commercially available from Esgee Technologies Inc.	
VPIC	[44]	3-Clause-BSD	Open Repo:[45]	doi:10.1063/1.2840133
VSim (Vorpal)	[46]	Proprietary	Available from Tech-X Corporation	doi:10.1016/j.jcp.2003.11.004
Warp	[47]	3-Clause-BSD-LBNL	Open Repo:[48]	doi:10.1063/1.860024
WarpX	[49]	3-Clause-BSD-LBNL	Open Repo:[50]	doi:10.1016/j.nima.2018.01.035
ZPIC	[51]	AGPLv3+	Open Repo:[52]	
ultraPICA		Proprietary	Commercially available from Plasma Taiwan Innovation Corporation.	

Wonder if there is not something here that could be useful to us?

References

[DAV73] Davies, A J ; Evans, C J., Yellow report CERN-73-10

[FON96] P. Fonte, IEEE Nucl. Sci. 43 n.3 (1996) 21

[GEO00] G.E. Georghiou et al., J. Phys. D: Appl. Phys. 33 (2000) 27.

[LIP04] C. Lippmann, W.Riegler, Nucl. Instrum. and Meth. A 533 (2004) 11

[Wiki1] By WikiHelper2134 - File:A_Comparison_Chart_For_Modeling_Plasma2.png, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=126786772 in https://en.wikipedia.org/wiki/Plasma_modeling