Simulation tools in plasma physics & astrophysics

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What is the minimum physics ?

- What is the plasma β value ?
- How collisional is the plasma ?
- What is the geometry/size of the system ?
- What are the temporal scales ?
- Do we have kinetic effects ?
- Do we have quantum effects ?
- Are radiative effects important ?

For LULI2000, (shot on `Cu` foil in 2017 w. J. Fuchs)

$n_e = 10^{26}$ m^{-3}, $T_e = T_i = 10^7$ K, $A = 63$, $Z = 29$
$B_{\text{ext}} = 50$ T

What is the plasma β value ?

• Magnetic field produced by external coils, up to 50 T
$\rightarrow$ produced on few ns [see e.g. *Albertazzi et al.*, 2013]

• Lasers on solid foil target
$\rightarrow$ with ns lasers : 100 eV
$\rightarrow$ with ps lasers : up to 15 MeV (with TNSA)

• Lasers on a gas
$\rightarrow$ heating with inverse Bremsstrahlung

✔ $P_m = 10^9$ Pa, $P_{i+} = 5 \times 10^8$ Pa, $P_{e^-} = 2 \times 10^{10}$ Pa
✔ $\beta \gg 1$ leaded by e^- ($\beta_{e^-} \sim 15$, $\beta_{i+} \sim 0.5$)

How collisional is the plasma ?

• Number of e^- in Debye sphere : $n_e\lambda_D^3 \sim 6 \times 10^3$
$\rightarrow$ Coulomb logarithm : $\ln\Lambda = \ln\left(\frac{\lambda_D}{\lambda_L}\right) = \ln(12\pi n_e\lambda_D^3) \sim 7$

Lorentz model : $\tau_e = \left[\frac{1}{(4\pi\varepsilon_0)^2}\frac{n_e e^4 \ln\Lambda}{m_e^{3/2}T_e^{3/2}}\right]^{-1} = 1\ \mu\text{s}$

Lorentz model : $\tau_i = \left[\frac{1}{(4\pi\varepsilon_0)^2}\frac{n_i Z^2 e^4 \ln\Lambda}{m_i^{3/2}T_i^{3/2}}\right]^{-1} = 1\ \text{s}$

✔ The plasma is collisionless (or weakly collisional)

What is the geometry/size of the system ?

- The systems are (of course) 3D and bounded

→ system size $\sim$ 1 mm

→ ion inertial length $\sim$ 30 μm

→ ion Larmor radius $\sim$ 30 μm

- ✔ meso-scale system w. $L/\rho_i \sim L/d_i \sim 10^3$
- ✔ but wave-length spectra reduced to 3 decades...

What are the temporal scales ?

• Gyro-frequency : $\Omega_{i+}^{-1} = 0.4$ ns.rad^{-1} (0.1 ps.rad^{-1} for electrons...)

• Plasma frequency : $\omega_{P,i+}^{-1} = 0.1$ ps.rad^{-1} (1 fs.rad^{-1} for electrons !)
$\rightarrow$ hence $\omega_{P,i+}/\Omega_{i+} \sim 10^3$ (like in solar wind, earth magnetosphere)

• Alfvén time $\tau_A = 1.6$ ns
$\rightarrow$ w. Alfvén velocity ~ 600 km.s^{-1} on $L \sim 1$ mm

✔ May allow most ion cyclotron effects
$\rightarrow$ but not the development of a turbulent cascad

Do we have kinetic effects ?

• The plasma is weakly collisional
→ not at thermal equilibrium
→ distribution functions can departe from Maxwellian

• Shocks, current sheets, plasma instabilities
→ wave-paticle interactions (Landau & cyclotron)
→ finite Larmor radius effects
→ can eventually break the Alfven theorem

✔ Kinetic effects can be important, at least for ions

Do we have quantum effects ?

- How Landau length compare to de Broglie length :

$$\lambda_L = \frac{Z_i}{12\pi n_e \lambda_{De}} = 10^{-11}\text{m}$$

$$\lambda_B = \frac{\hbar}{\sqrt{m_e k_B T_e}} = 2 \times 10^{-11}\text{m}$$

✔ Quantum effects are not at play...
$\rightarrow$ essentially because the plasma is collisionless !

Are these regimes radiative or not ?

- Ratio between plasma kinetic energy and radiative energy :

$$\frac{e}{E_r} = \frac{P/(\gamma - 1)}{(4\sigma/c)T^4} \ll 1 \qquad \text{: Mihalas number}$$

- Ratio between plasma kinetic flux and radiative flux :

$$\frac{\phi_e}{F_r} = \frac{ve}{\sigma T^4} ve = \frac{v}{c}\frac{e}{E_r} \sim 1 \qquad \text{: Boltzmann number}$$

✔ radiative effects can oftenly be omitted
$\rightarrow$ but the plasma is not a black body and eventually optically thick

The EM part (curl) of a plasma code

• Maxwell-Faraday : $\partial_t \mathbf{B} = -\boldsymbol{\nabla} \times \mathbf{E}$

→ this equation is always solved except for ES codes
→ eventually in a different form like $\partial_t \mathbf{B} + \boldsymbol{\nabla}.(\mathbf{UB} - \mathbf{BU}) = 0$

⚠ Might eventually need a correction to ensure a divergence-free $\mathbf{B}$ field

• Maxwell-Ampère : $\partial_t \mathbf{E} = c^2 \boldsymbol{\nabla} \times \mathbf{B} - \varepsilon_0^{-1} \mathbf{J}$

→ for modes with $\omega / k \ll c$: Darwin approximation
→ neglect the transverse component of the displacement current

⚠ The longitudinal component of the displacement current is still here... hopefully !

The EM part (divergence) of a plasma code

Both of these equations appear as "initial conditions" :

- Maxwell-Thomson : $\boldsymbol{\nabla}.\mathbf{B} = 0$

$\rightarrow$ such error can increase in time
$\rightarrow$ wrong topology of the B-field lines $\Rightarrow$ orthogonal plasma transport
$\rightarrow$ "constrained transport methods" : special discretization of the B field
$\rightarrow$ "Hodge projection" in Fourier space (👎 domain decomposition)

- Maxwell-Gauss : $\boldsymbol{\nabla}.\mathbf{E} = \rho/\varepsilon_0$

$\rightarrow$ with a Boris correction $\mathbf{E}^\star = \mathbf{E} + \boldsymbol{\nabla}\phi$ so that $\boldsymbol{\nabla}.\mathbf{E}^\star = \rho/\varepsilon_0$
$\rightarrow$ solve Poisson $-\Delta\phi = \boldsymbol{\nabla}.\mathbf{E} - \rho/\varepsilon_0$ (Marder method w. diffusion eq.)
$\rightarrow$ "structure preserving discretization" (Esirkepov method)
charge and current densities not deposited in the same way

Fluid codes : Maxwellian plasma ?

• Hypothesis and approximations :

$$
\begin{aligned}
\partial_t n + \boldsymbol{\nabla}.(n\mathbf{V}) &= 0 && (1)\\
nm(\partial_t \mathbf{V} + \mathbf{V}.\boldsymbol{\nabla}\mathbf{V}) &= nq(\mathbf{E} + \mathbf{V} \times \mathbf{B}) - \boldsymbol{\nabla}.\mathbf{P} + \eta\mathbf{J} && (2)
\end{aligned}
$$

• One needs a closure equation
$\rightarrow$ generally on a scalar pressure, isothermal (isotropic) or adiabatic

• Then the species are only described by the first 3 moments, n, $\mathbf{V}$ & P

✔ It does not mean that the plasma is maxwellian (that is eventually collisional), but it means that higher moments ($\mathbf{Q}$, $\mathbf{R}$...) are not needed to describe the physical evolution of the system

Fluid codes : Darwin approximation

• Any charge separation would need to solve a Maxwell-Gauss equation
→ hence, a local density defined on a whole cell is not enough

✔ No way to solve any charge separations with a fluid formalism

• We then always have the Darwin approximation for fluid formalisms
→ but some electrostatic modes still exist... like eg Ion Acoustic Waves
→ the compressional character of the plasma is still handled !

✔ Fluid codes then always need an Ohm's law

Fluid codes : Ohm's law

• While $\mathbf{E}$ field is needed in Maxwell-Faraday, one needs an Ohm's law
$\rightarrow$ it has to be the one associated to the massless electrons

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \frac{1}{en}(\mathbf{J} \times \mathbf{B} - \boldsymbol{\nabla}.\mathbf{P}_e) - \frac{m}{e} d_t \mathbf{V} + \frac{m}{e} d_t \left(\frac{\mathbf{J}}{ne} \right) + \eta \mathbf{J} - \eta' \Delta \mathbf{J}$$

• The electron fluid velocity results from the ion velocity and total current

• The pressure is the electron one... hence needing a closure equation

✔ Dissipative terms can be physical and/or numerical (for stability)

Fluid codes : general features

- The MHD fluid can be relativistics
- The $\eta\mathbf{J}$ term is associated to e^-/p^+ collisions
- p^+/p^+ collisions conserve momentum and energy for ellastic collisions

$\rightarrow$ nothing to add in the fluid equations...

- The dissipative term can be anomalous

$\rightarrow$ "contain" various physical process like EM fluctuations...

- No characteristic length, only the Alfvén velocity

$\rightarrow$ this can complicate the comparison between codes

Fluid codes : bi-fluid and Hall MHD

• Bi-fluid codes have then to be "hybrid"
$\rightarrow$ needs a closure equation for the "second" fluid (that is the e^-)

✔ bi-fluid codes w. different closure for the 2 fluids (& current density)

• Another approach is the Hall-MHD
$\rightarrow$ the single MHD fluid can then let some current develop
$\rightarrow$ this current results from the slip between p^+ and e^-
$\rightarrow$ the Hall-MHD equations are then parabolic (and not anymore hyerbolic)

• electron MHD (e^- inertia-less, see *Kingsep et al.*, 1987)
$\rightarrow$ total current given by electron velocity in non-moving background ions

Fluid codes : single fluid (MHD)

• MHD is a single fluid : summation over all species.
$\rightarrow$ then, the $\mathbf{E}$ field disappears from momentum equation by quasi-neutrality

⚠ The closure is for this single fluid... no way to discriminate p^+ & e^-

• Ideal MHD for $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$
$\rightarrow$ the plasma is collisionless
$\rightarrow$ low k and ω values, that is $kL \ll 1$ and $\omega\tau \ll 1$
$\rightarrow$ Alfvén theorem : plasma and B field are frozen together

Fluid codes : algorithms

• MHD codes are oftenly written in a conservative form
→ use of finite volume methods on a structured grid
→ Godounov formulations (*Godunov*, 1959) are then very popular
→ TVD schemes (with flux limiters) for discontinuities
→ for such explicit schemes, one needs to satisfly the CFL conditions

• With strong gradients ⇒ that is converging characeristics
→ eventual use of Lagrangian approach on an unstructured moving mesh
→ closure equations might not be local

Fluid codes : brief overview of few (french) MHD cdes

• `RAMSES` : Romain Teyssier
→ cartesian AMR grid, include self-gravity and cooling (eventually particles)

• `Heracles` : Edouard Audit
→ cartesian/cylindrical/spherical fixed grid for hydro, MHD, hydro-rad, self-gravitating flows

• `Gorgon` : Andrea Ciardi
→ cartesian MHD including vaccuum

• `FCI2` : Alain Grisollet
→ hydro-rad with laser energy deposition using a Lagrangian approach

Vlasov codes : governing plasma equation

• The Vlasov equation can be written for any Hamiltonian system
→ start with the Boltzmann equation & neglect the collision operator

• Each species are then described by a Vlasov equation

$$\partial_t f_s + \mathbf{v}.\partial_{\mathbf{r}} f + \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v}_s \times \mathbf{B}).\partial_{\mathbf{v}} f_s = 0$$

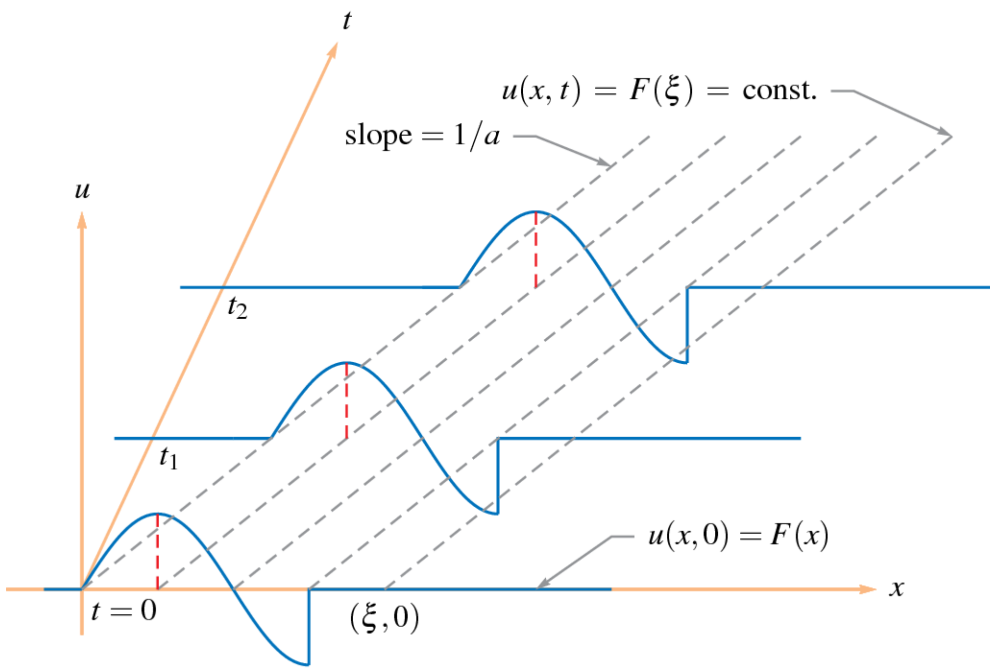
• The distribution function should then be noiseless
→ the tail of the distribution is described as well as the core

• The plasma-ElectroMagnetic field system can be closed in 2 ways
→ Vlasov-Poisson for electrostatic problems
→ Vlasov-Maxwell for electromagnetic problems

Vlasov codes : conservative form

- The Vlasov equation is fundamentally a hyperbolic conservative equation

$\rightarrow \partial_t u + a\nabla u = 0$



$\rightarrow$ Finite volume techniques should then be well suited

Vlasov codes : use of characteristics ?

• Fillamentation where characteristics are converging in phase space
$\rightarrow$ needs some numerical cautions : Euler solvers can then be challenged

• Lagrangian approach
$\rightarrow$ a sample of the distribution function is followed in the same way as a macro-particle

• semi-Lagrangian approach
$\rightarrow$ a new sampling on a uniform Eulerian grid is performed

• The Liouville's theorem imply mass, momentum, energy... conservation

Vlasov codes : numerical cost

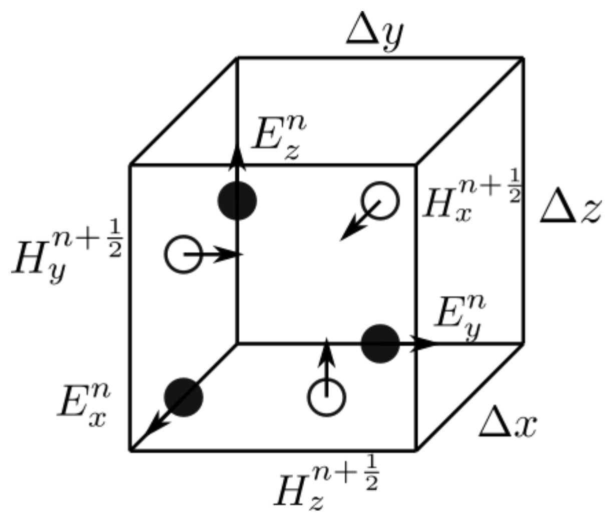
• $f_s(\mathbf{r}, \mathbf{v}, t)$ depends on 7 unknowns that have to be discretized

• Simulation (Eulerian) of the Earth magnetosphere : 10^{18} cells...
$\rightarrow$ 8 ExaBytes of RAM memory ! out of reach, even in far future...
$\rightarrow$ now, we can go up to 10^{12} sample points
PIC : [Daughton et al., 2011], Vlasov : [Palmroth et al., 2017]

• Different solutions are possible :
$\rightarrow$ use a sparse grid representation
$\rightarrow$ drop the azimuthal velocity dimension (gyrokinetic approach) for gyrotrop distributions
$\rightarrow$ reduce the grid resolution in less important areas (of phase space)
$\rightarrow$ pruning the phase-space : remove grid elements in low density regions
$\rightarrow$ adapt the coordinate system like $v_\parallel$, $v_\perp$, v_ϕ & lower resolution of v_ϕ

Vlasov codes : FDTD algorithms

• The Finite-Difference Time Domain (FDTD) approach has became a standard in plasma EM simulation
→ Maxwell equations staggered in space with Yee lattice [*Yee*, 1966]
→ the scheme is time centered with a leap-frog technique [*Verlet*, 1967]



• The Vlasov equation is Lorentz-invariant, provided the velocity is correctly handled

Vlasov codes : brief overview of few (non-french) Vlasov

• `Vlasiator` : Mina Palmroth
$\rightarrow$ collisionless hybrid-Vlasov code essentially for magnetosphere & space weather

• `Impacta` : Robert Kingham
$\rightarrow$ 2D, implicit, with a linearized version

PIC codes : macro-particles

• Instead of using a distribution function, one can use a piece of it
→ a macro-particle is a "sample" of the distribution function

• The equations of motion of a macro-particle are simply :

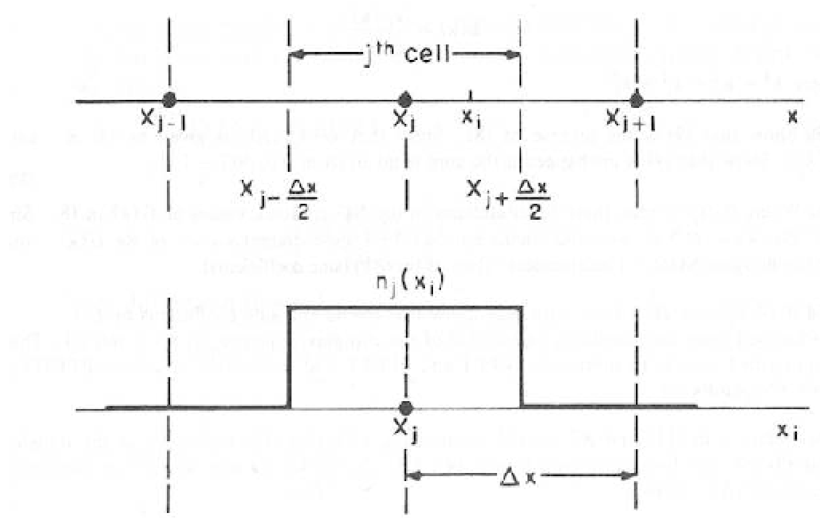
$$d_t\mathbf{r} = \mathbf{v} \quad , \quad d_t\mathbf{v} = q/m(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

→ characteristics of the Vasov equation for Liouville's theorem

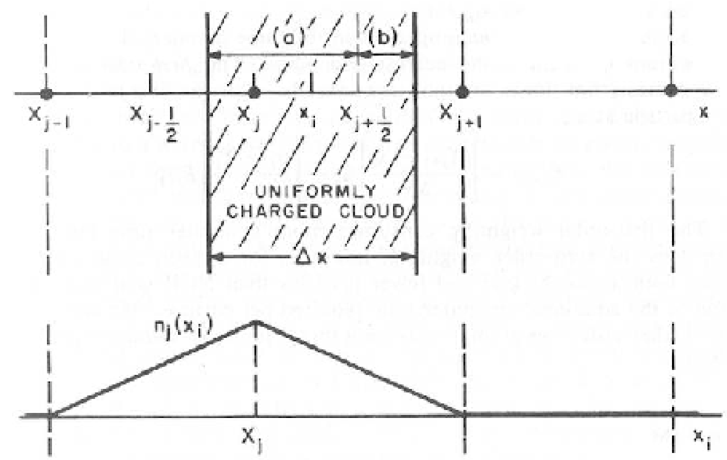
• The Klimontovitch equation on $f^K(\mathbf{r}, \mathbf{v}, t) = \sum_{i=1}^{N} \delta(\mathbf{r} - \mathbf{r}_i(t))\delta(\mathbf{v} - \mathbf{v}_i(t))$ can not be handled as is, because of the δ's
→ as usually done in statistical physics, $f(\mathbf{r}, \mathbf{v}, t) = \langle f^K(\mathbf{r}, \mathbf{v}, t)\rangle_{\text{ensemble}}$
→ but how to deposit the δ values on the grid ?
→ the magnetic & (Debye shielded) electric field are calculated on a grid

PIC codes : shape factor (assignment function)

- Assignment function is generally a b-spline function of order 1, 2 or 3



(a) Zero-order weighting



(b) First-order weighting

→ support of an assignment function has to be larger than the grid size

PIC codes : shape factor (assignment function)

• The shape factor is the local value of the assignment function
$\rightarrow$ hence the charge density and momentum,

$$\rho(\mathbf{r}) = q \sum_{i=1}^{N} w_i S(\mathbf{r} - \mathbf{r}_i) \quad , \quad \rho(\mathbf{r})\mathbf{U}(\mathbf{r}) = \sum_{i=1}^{N} w_i \mathbf{v}_i S(\mathbf{r} - \mathbf{r}_i)$$

• Physical and numerical involvements
$\rightarrow$ The larger the b-spline order, the better the code stability
$\rightarrow$ The narowwer the b-spline, the deeper the density gradients

• Large dispariries in the w_i's values should allow to investigate large density gradients

PIC codes : particle management

• In a given cell, the number of particles N_G is oftenly of the order of 100
$\rightarrow$ not enough to properly describe the tails of the distribution function
$\rightarrow$ need to consider ghost cells to correctly build the fluid moments
$\rightarrow$ this can strongly burden the code efficiency

• For 3D system, the # of macro-particle is dramatically RAM consuming
$\rightarrow$ 80% of CPU time to push [*Boris*, 1973] & deposit particles on the grid

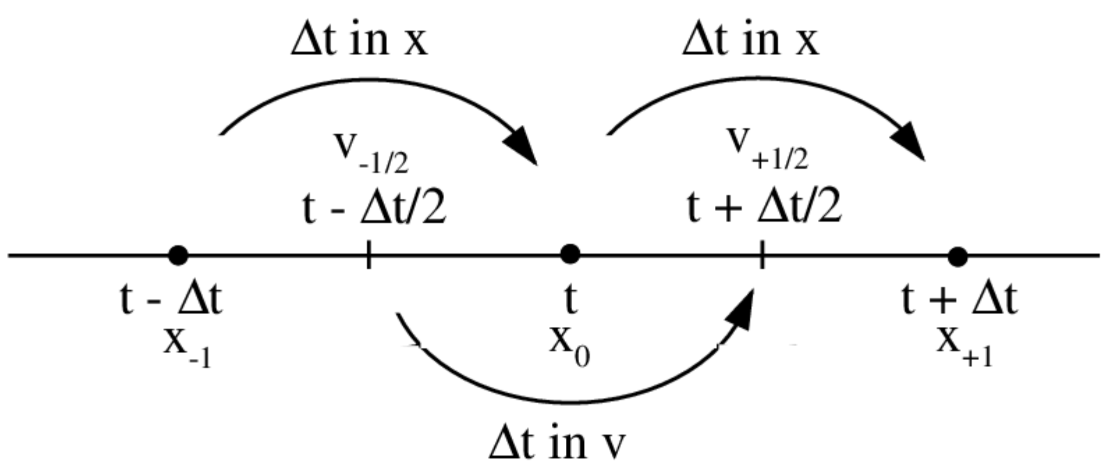
• Coulomb collisions with other particles using Monte-Carlo methods [*Takizuka & Abe*, 1984]
$\rightarrow$ then consider that total CPU time is multiplied by a factor 2

• For statistical reasons, need to split or merge particles when needed
$\rightarrow$ some techniques exist, but can be specific [*Smets et al.*, 2021] or time consuming [*Gosnokov*, 2021]

PIC codes : algorithms

- FDTD (Finite Difference Time Domain) methods are widely used

→ method of second order in both space and time
→ space centering oftenly resulting from the use of a [*Yee*, 1966] lattice
→ time centering results from the use of leap-frog schemes [*Verlet*, 1967]



PIC codes : full-PIC & hybrid-PIC

• Full-PIC codes manage both p^+ and e^- as paticles
$\rightarrow$ resolve the charge separation with Maxwell-Gauss equation
$\rightarrow$ generally dedicated to problems where the e^- play a central role
$\rightarrow$ typical scales (& normalization) are then ω_{Pe}^{-1}, λ_{De}, and need c/V_A
$\rightarrow$ can easily be relativistic at a modest cost
$\rightarrow$ one generally cheat with mass ratio m_p/m_e and/or c/v_A
$\rightarrow$ well-fitted to study pair-plasmas

• Hybrid-PIC codes manage p^+ as particles and e^- as a massless fluid
$\rightarrow$ hence, this approximation means $m_e/m_p \rightarrow 0$ (opposite to full-PIC)
$\rightarrow$ one then needs an Ohm's law and a closure equation for the electrons
$\rightarrow$ typical scales (& normalization) are then Ω_p^{-1}, l_p, and $c/V_A \rightarrow \infty$
$\rightarrow$ none of electron scales can be handled... unless some efforts [*Sladkov et al.*, 2021]

PIC codes : brief overview of (french) PIC codes

• `Smilei` : M. Greck
→ field ionization, binary collisions and impact ionization, QED processes, such as high-energy photon emission and its back-reaction on the electron dynamics, as well as pair production through the Breit-Wheeler process

• `Zeltron` : B. Cerutti
→ general relativity & radiation reaction force including synchrotron and inverse Compton back-reaction force

• `PHARE` : N. Aunai
→ Hybrid-PIC, still in development, using AMR (`SAMRAI`) and many more nice upcoming features !

Radiative part of a (fluid) plasma code

• The radiative transfer equation should be solved for the specific intensity $I(\mathbf{r}, t, \mathbf{n}, \nu)$
$\rightarrow$ This equation contain absorption, emmisivity and diffusion coefficients

• One can wether deal with the moment of order 0, 1 & 2 of this equation
$\rightarrow$ 3 equations on the radiative energy density, radiative energy flux & radiative pressure tensor

[*Mihalas & Mihalas*, 1984]

• As for plasma fluids, the system needs to be closed
$\rightarrow$ M1 approximation [*Levermore*, 1984] : $\mathbb{P}_0 = \frac{1}{2}E_0[(1-f)\mathbb{I}+(3-f)\mathbf{n}_0\mathbf{n}_0]$
$\rightarrow$ Flux-Limited-Diffusion [*Alme & Wilson*, 1973] : $\mathbf{F}_0 = -K\boldsymbol{\nabla}E_0$

✔ E_0 and $\mathbf{F}_0$ are then source terms in fluid equations...

Units and free parameters

• "Modern" codes are always unit-less (?)
$\rightarrow$ but scales discrepencies of physical origin are unavoidable
$\rightarrow$ No spatial characteristic length scale in MHD
$\rightarrow$ length scales can be the inertial length or the Debye length (p^+ or e^-)

• Vaschy-Buckingham theorem : N variables & 4 units
$\rightarrow$ need $N-4$ dimensionless parameters for characterizing a simulation

• MKS system was adopted in commerce and ingeneering in 1889, extended to MKSA in 1901 and published in 1960
$\rightarrow$ consider that CGS-Gaussian is not the only possibility to include electromagnetism in CGS
$\rightarrow$ in CGS, pressure in Barye, viscosity in Poise and wavelength in Kayser, electric charge in Franklin...

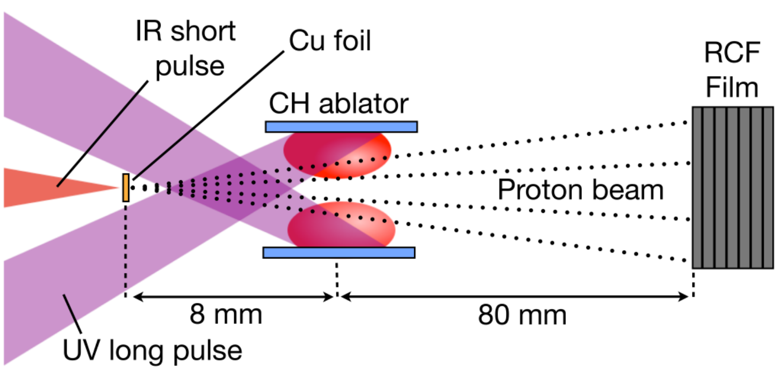
Engineering of plasmas codes

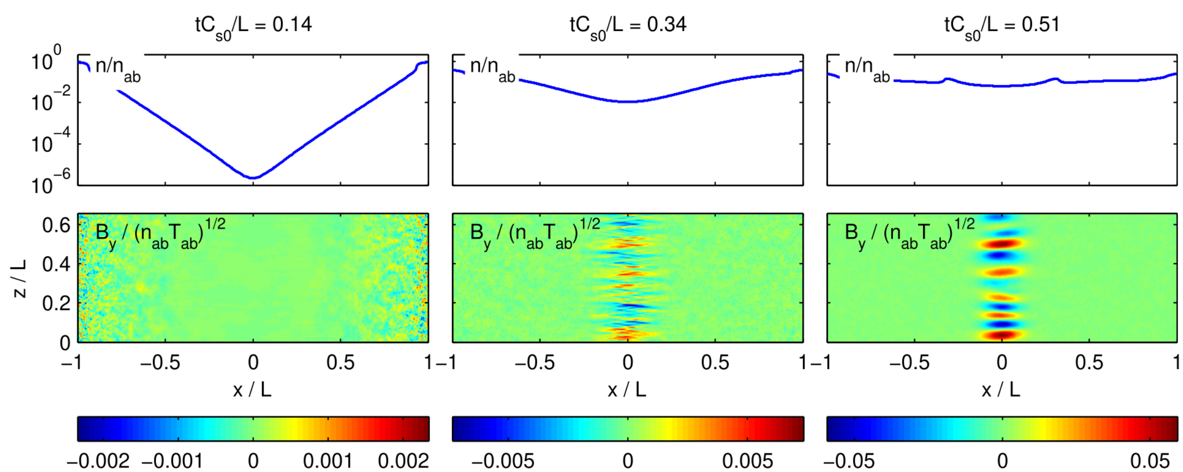
- domain decomposition
- run on HPC and exascale ready... (?)
- open sources or at least open to the community
- using a versioning system as GIT
- including unitary, functional & non-regressive tests
- generally working together with continuous integration
- written in a "long living" language, dedicated to 21st century challenges
- with "clean code" practices & design-patterns
- efficient for present (CPU) and future (GPU ?) architectures

Weibel instability

• Mediated by temperature anisotropy or multiple counterstreaming beams
→ ablation density feeded at open boundary conditions
→ characteristic wavelength of the order of ion inertial length

[*Fox et al.*, 2013]





Biermann-battery effects

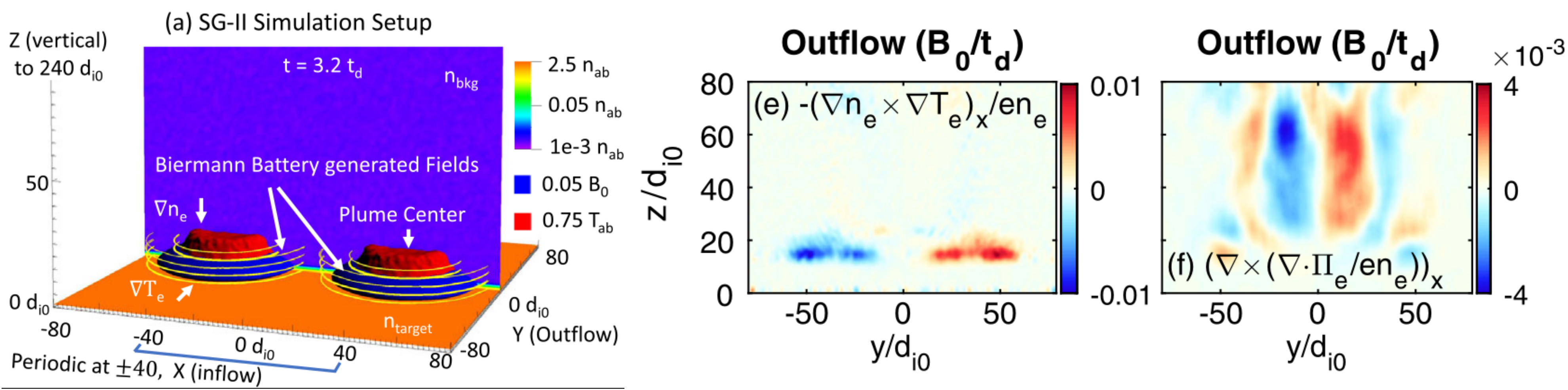
- Growth of seedless (clockwise) magnetic field, $\partial_t \mathbf{B} = -(en_e)^{-1} \nabla n_e \times \nabla T_e$

$\rightarrow$ can generate magnetic field up to 100$^{\text{th}}$ of Teslas in HEDP

- Density and temperature gradient (for e^-) feeded by ad-hoc operator

$\rightarrow$ modify the compression of the CS, and the reconnected flux pattern

[*Matteucci et al.*, 2018]



✔ The Biermann-battery effect contributes to the reconnected flux generation

Nernst & Righi-Leduc effects

- For e^- heat transport, Spitzer-Härm breaks down : $\lambda_{\text{mfp}} > T_e/\nabla T_e$

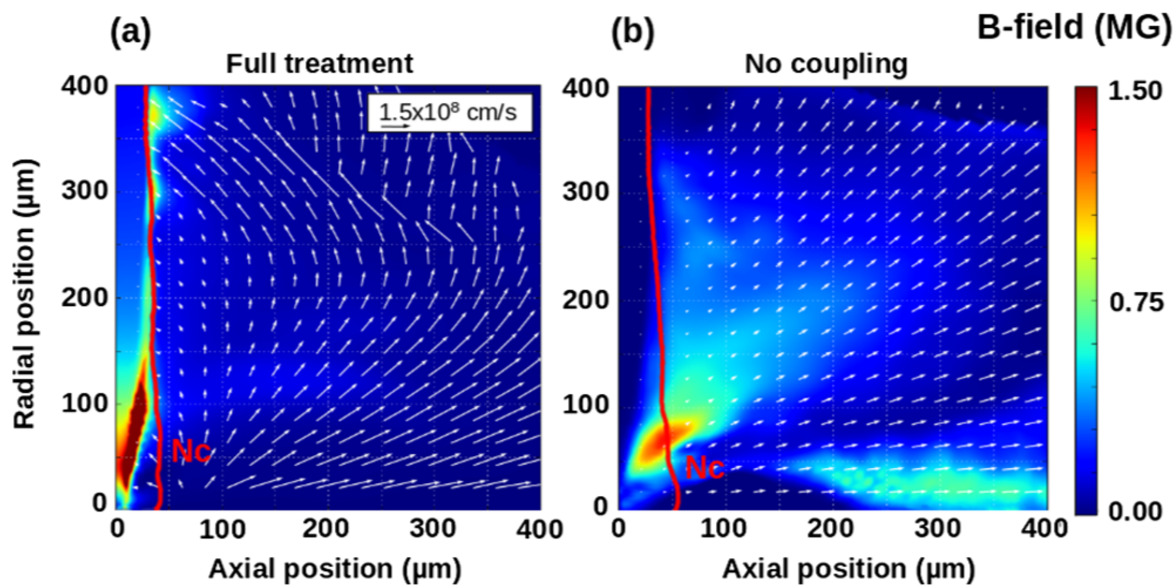
$\rightarrow$ non-classical heat flow modifies the Nernst advection effect

$\rightarrow$ B-field advection & compression in denser region : $\mathbf{q}_e = -\kappa\mathbf{B} \times \boldsymbol{\nabla} T_e$

$\rightarrow$ Nernst (radial) advection underestimated by [*Braginskii*, 1965]

$\rightarrow$ $\mathbf{q}_e$ needs to be non-local so that $\mathbf{U}_{\text{Nernst}} = (\gamma - 1)\mathbf{q}_{\text{NL}}/p_e$ is realistic

[*Lancia et al.*, 2014]

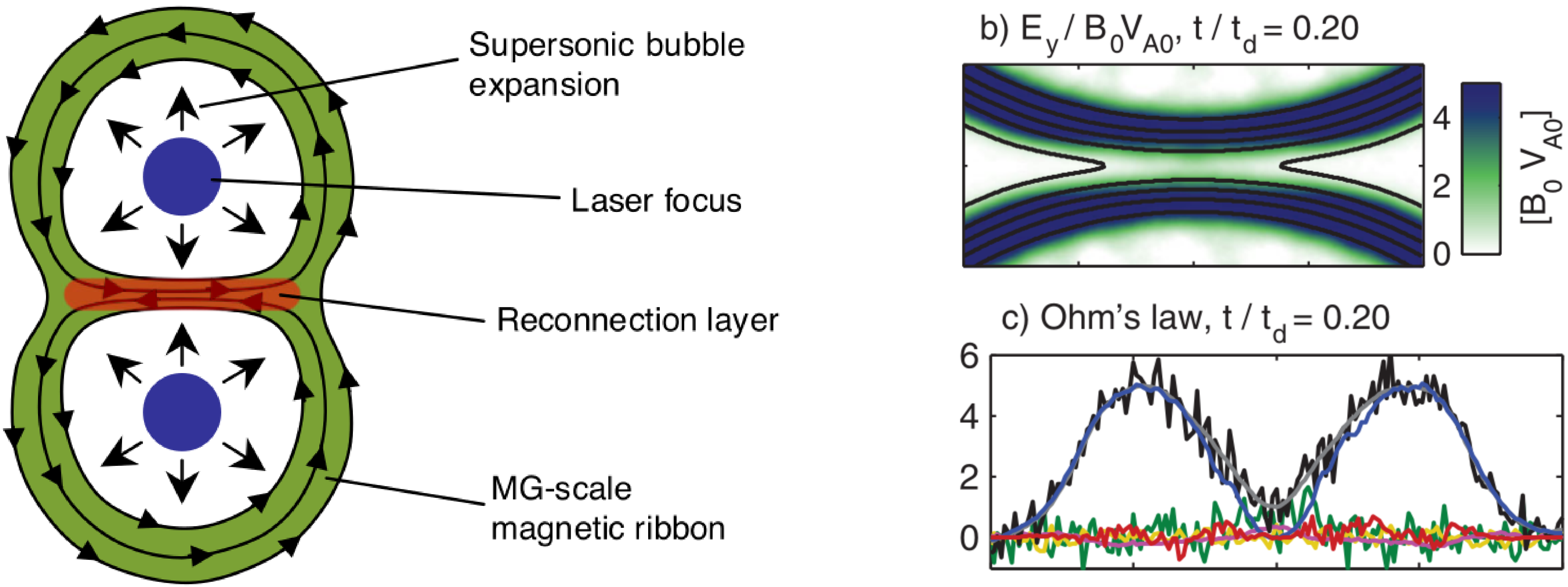


Magnetic reconnection

- Two opposing magneic bubbles squeeze together and then reconnect

$\rightarrow$ strong inflow can drive "flux-pileup" reconnection

[*Fox et al.*, 2011]



Nernst effects for reconnection

- Electron Ohm's law results from 1$^{\mathrm{st}}$ order moment of Vlasov-FP

$\rightarrow$ B-field frozen in the hot collisionless electrons

$\rightarrow$ it is not associated to current (driven by the cooler electrons)

$\rightarrow$ importance of Nernst advection compared to Hall effect in reconnection

[*Joglekar et al.*, 2014] with Vlasov code, [*Kingham et al.*, 2004]

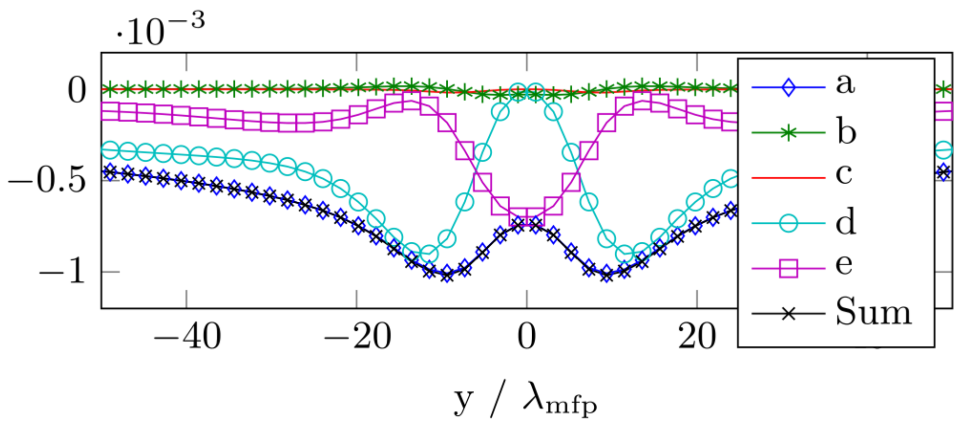


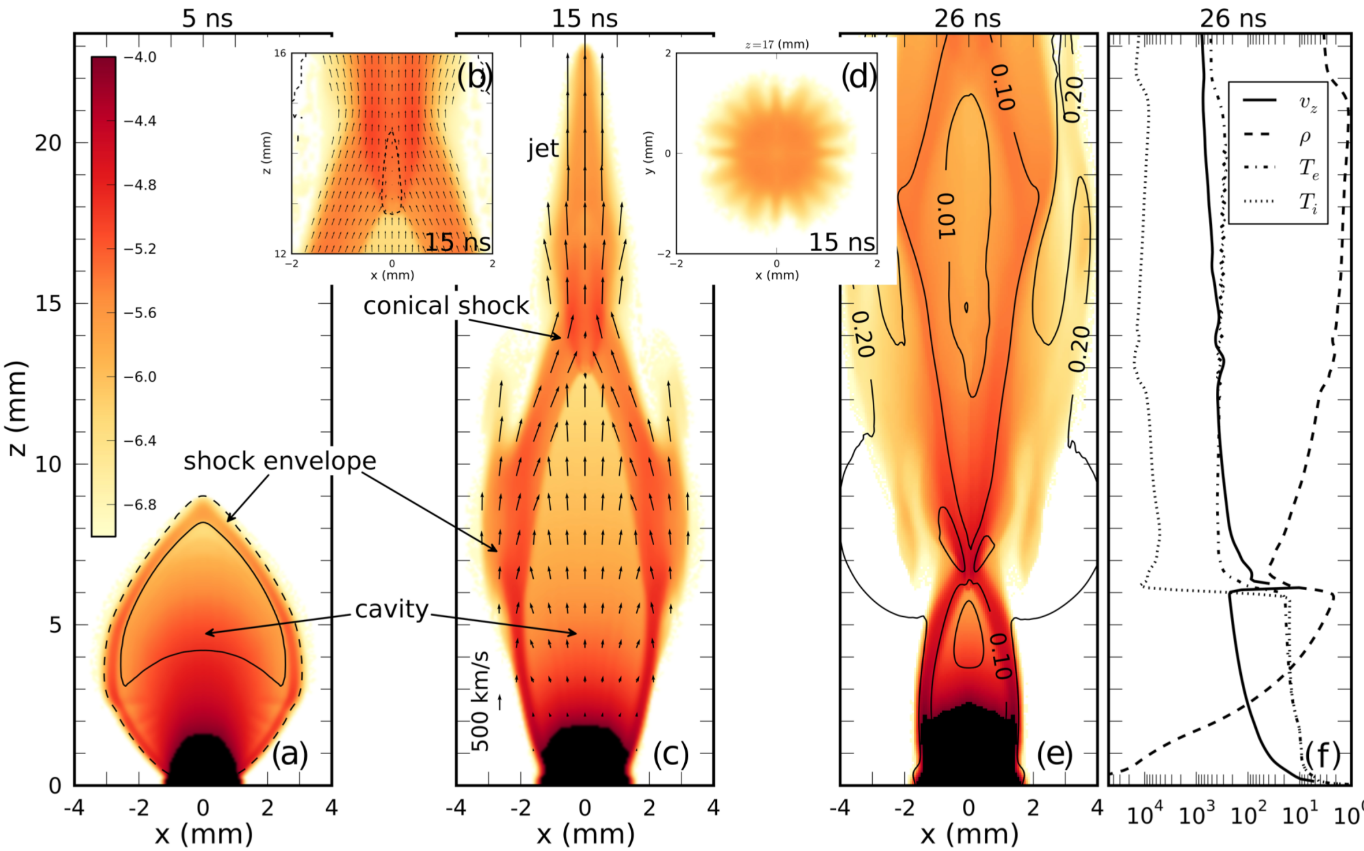
FIG. 2 (color online). Illustration of the contribution of the different components of Ohm's law in Eq. (2) taken from the simulation at a time $t = 11000\tau_n$. (a) E_z calculated from the code, (b) $\bar{\eta} j_z$, (c) $[\mathbf{j} \times \mathbf{B}]_z$, (d) $[\mathbf{v}_T \times \mathbf{B}]_z$, (e) $[(\nabla \cdot \langle \mathbf{vv}v^3 \rangle)/(2\langle v^3 \rangle)]_z$. (f) Sum of all contributions (b)–(e).

Collimation of plasma jets

• recollimation of wide-angle winds from stars and discs

→ differential rotation of the poloidal B field ⇒ B_θ collimate the jet

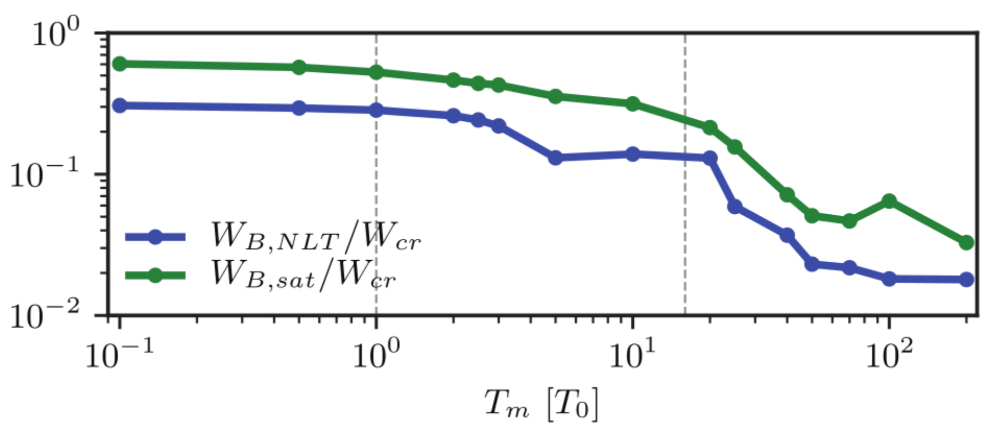
[*Ciardi et al.*, 2013]

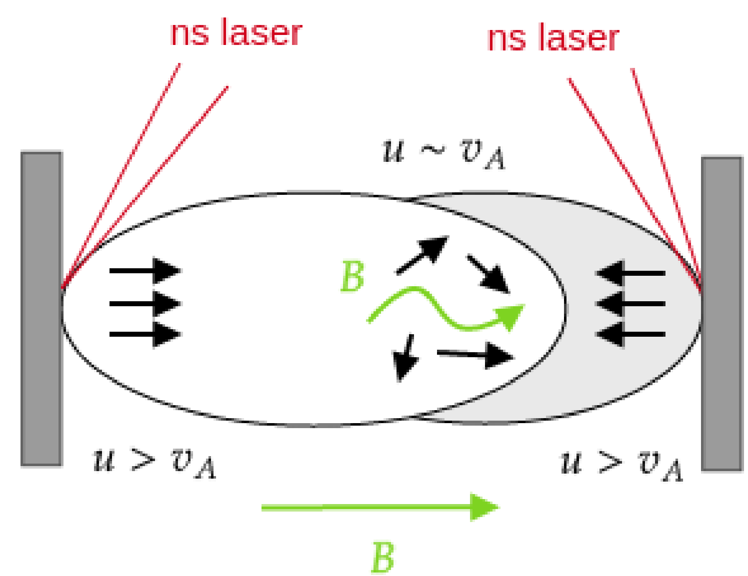


Beam-plasma instability

• [*Bell*, 2004] instability (NR) can drive large B fluctuations
→ decrease of B field saturation level with temperature
→ the growth rate of the instability can increase with collisions

[*Marret et al.*, 2021]





Concluding remarks

• Wide range of laser-based lab. experiments with pros. & cons. :

👍 These experiments are reproducible
👍 They are far less expensive than in-situ or remote measurements
👍 They are faster to achieve (less than a PhD thesis duration)
👍 They are less risky than space mission with satellites & probes

But...

👎 Not that easy to rescale with appropriate unitless numbers
👎 They are quite hard to investigate with dedicated diagnostics
👎 Need numerical simulations to disentangle the results

$\rightarrow$ The astrophysical community needs to think about the growing opportunities of laser-based laboratory experiments
$\rightarrow$ keep in mind that 10^6 CPU hours means 4 tons of CO_2 !