PIC simulation at boundaries of comets

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08 November 2023

Why is a plasma physicist interested in comets?

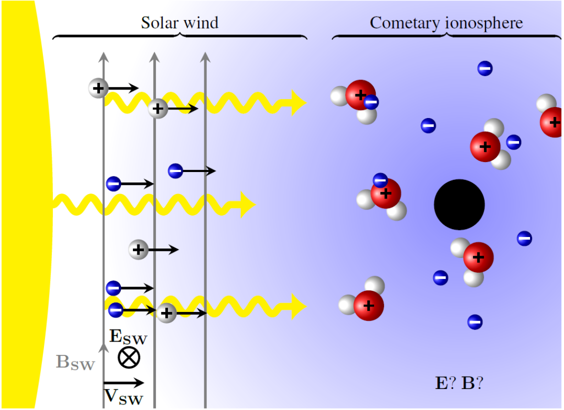

Figure: Beth et al. 2022, chapter in Comets III, to be published

- Neutral gas environment dominated by H_2O and CO_2, ionised by solar photons and energetic electrons (e.g. accelerated SW electrons, source of auroras, Galand et al. 2020)
- As the distance to the Sun evolves, comets develop a denser and more extended ionosphere
- Plasma boundaries and regions form as the activity goes up: bow shock, cometosheath, diamagnetic boundaries

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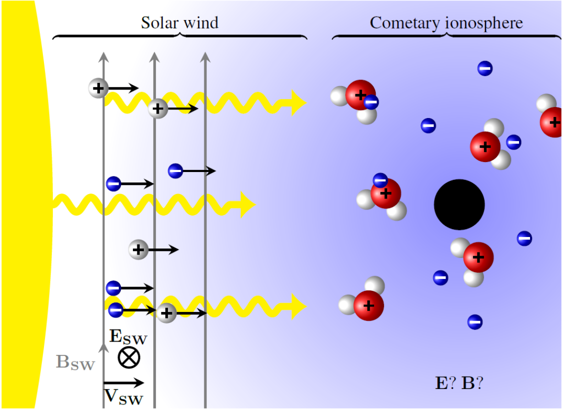

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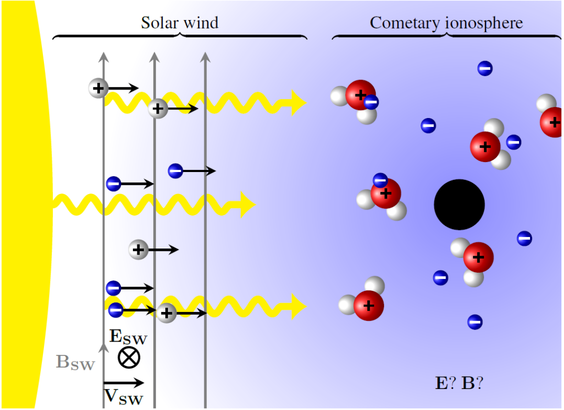

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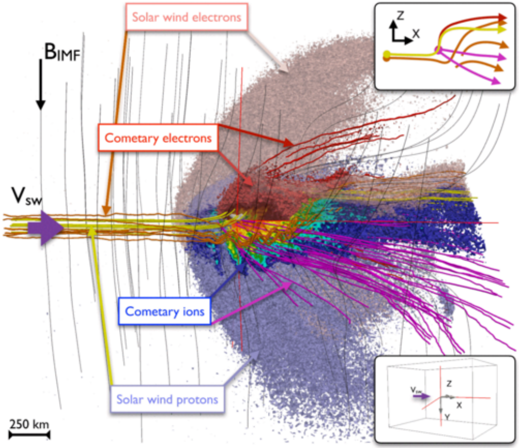
Comet-SW interaction at low activity



- Large scale simulation with iPIC3D (Deca et al. 2017, $m_i/m_e = 100$)
- Collisionless interaction mediated through the fields between a fast light plasma and an heavy slow one replenished over time
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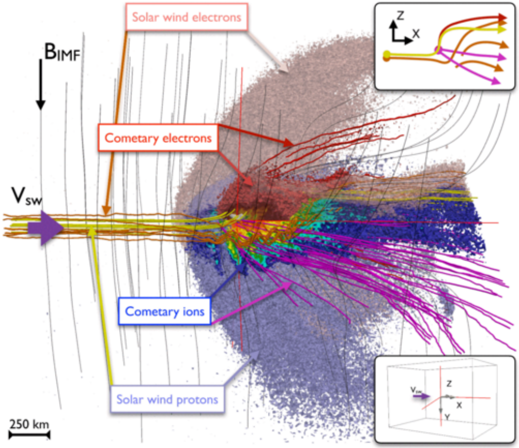

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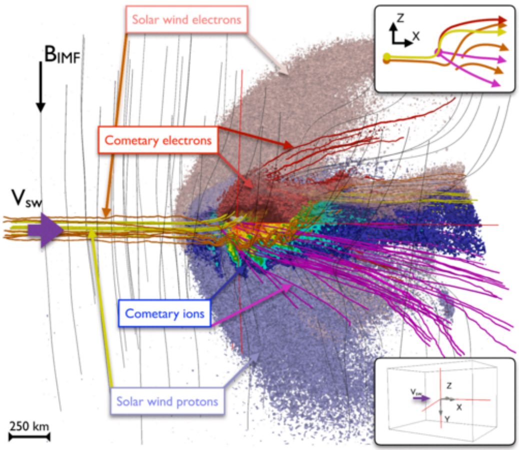

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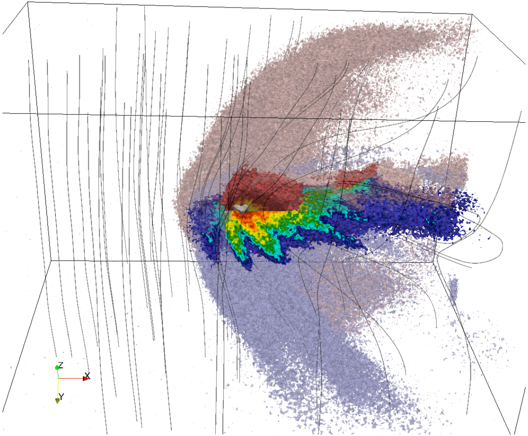
An animation for the eyes



Comet-SW interaction at large activity

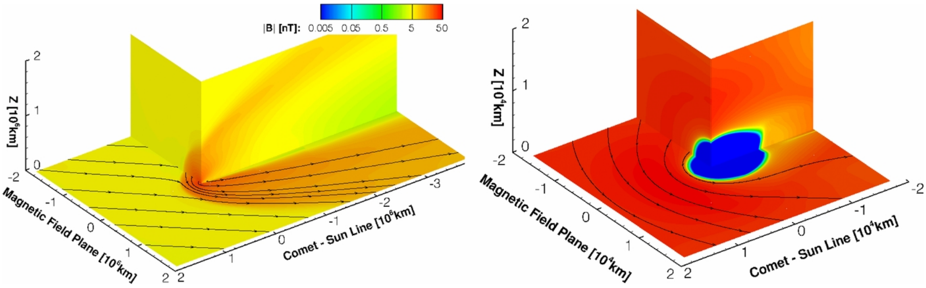


Figure: Modelled magnetic field around 1P/Halley, Rubin et al. 2014

- For higher activity, we need a more MHD-like approach (larger scale, collisional)
- Even if the comet is unmagnetised, the magnetic field starts to drap, pile-up, a bow shock forms, as well as a cometosheath, and a region with no or extremely weak magnetic field (< 0.1 nT)

Plasma interaction as a function of time

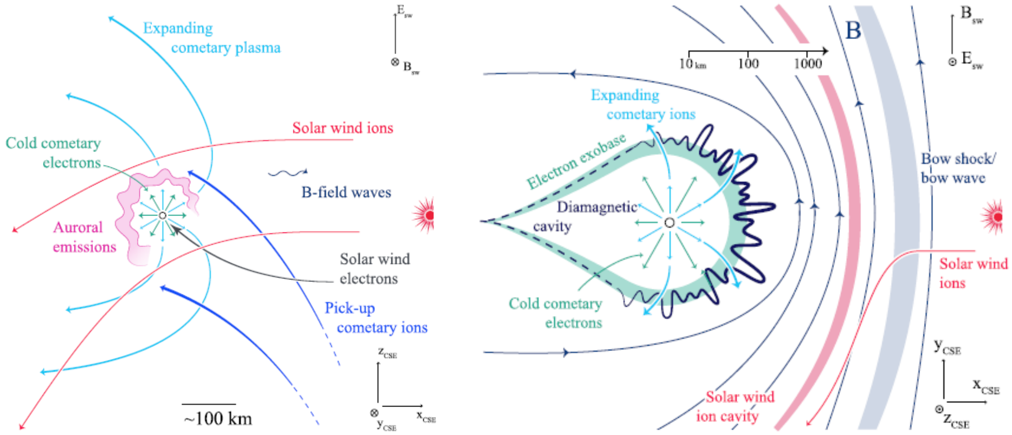


Figure: Schematic of the interaction at different activity (Goetz et al., 2022)

The diamagnetic cavity: a puzzling region

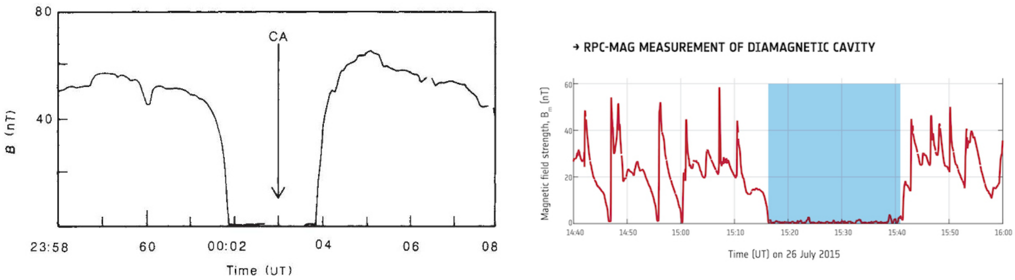


Figure: Magnetic field during diamagnetic cavity crossings

What is the pressure balance or properties at the kinetic scales that maintain this boundary?
Is it different depending on the activity?
What are the phenomena occurring down to the electron scale that are not captured by MHD/Hybrid model (anisotropy, electron pressure tensor)?

Using SMILEI for the diamagnetic cavity boundary (Beth+ 2022)

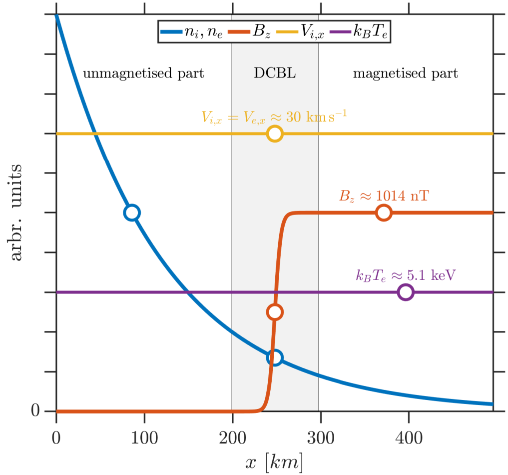


Figure: Initial setup

$$\underbrace{c\Delta t \leq \overbrace{\Delta x}^{\text{no instability}} }_{\text{CFL}} \leq \underbrace{\lambda_{e,\mathrm{De}} \ll L_{e,sd}}_{k_B T_e \ll m_e c^2} \ll N_{\mathrm{cell}} \Delta x$$

and

$$\omega_{pe} \Delta t \leq \sqrt{\frac{k_B T_e}{m_e c^2}}$$

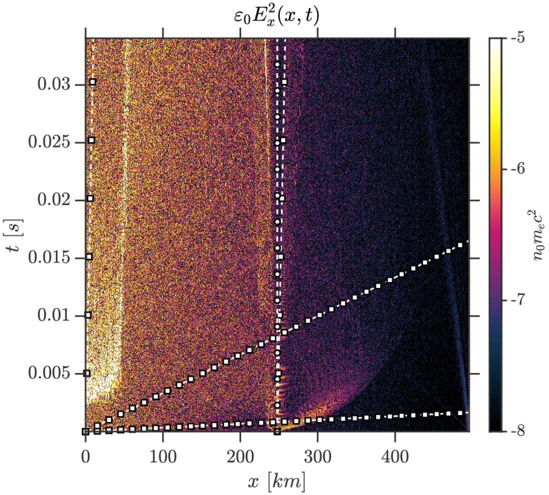
Scaling was necessary because I was limited in CPU time: 50 000 hr / month (please do not laugh)

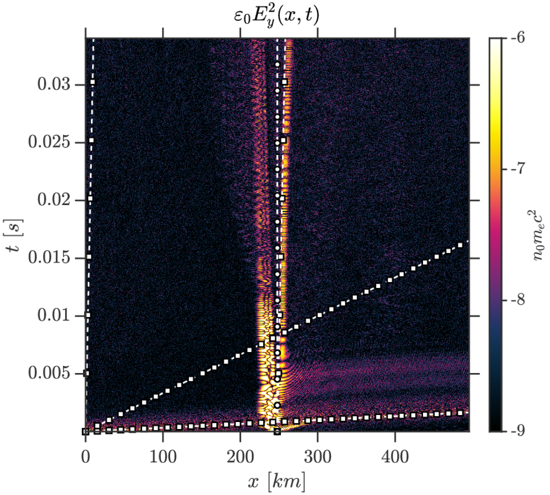
Some warnings

- Ions and electrons are not replenished over time with photoionisation (not very handy with SMILEI)
- $n_i \approx \exp(-x/H)$ while $n_i \approx 1/r$ at comets $\Longrightarrow$ it allows to have a constant and very well knowm ambipolar field through the box $-\nabla P_e/qn_e \approx$ constant
- $T_e = 10$ eV at comets $\Longrightarrow \lambda_{e,D}/L_{e,sd} \approx 0.01$ in reality (10 here)

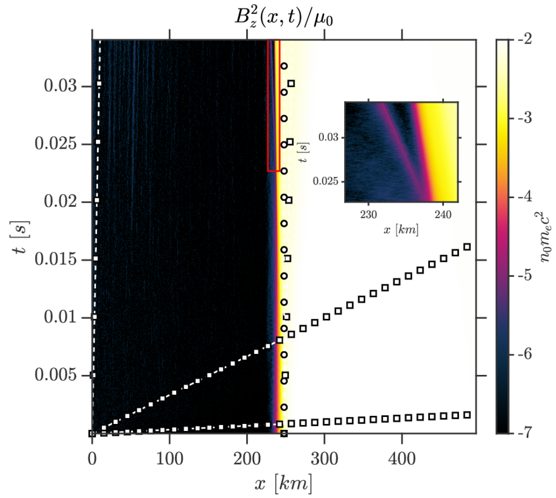
There was not a real aim to reproduce phenomena but more understanding the phenomenon

Electric pressure E^2





Magnetic pressure B^2



- E_x^2: larger fluctuations in the unmagnetised part to be compared with the ambipolar field

$$\frac{< E^2 >}{< E >^2} \approx \frac{1}{\Lambda} \frac{H_p^2}{\lambda_{e,De}^2}$$

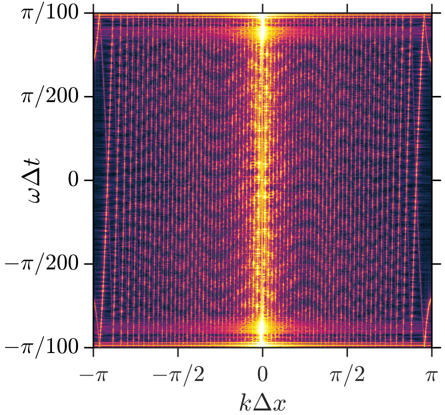
H_p is the plasma scale height

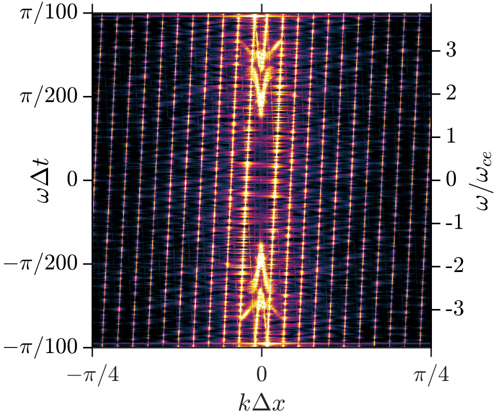
- E_y^2 and B_z^2 are coupled

$$\partial_t(\varepsilon_0 E_y^2 + B_z^2/\mu_0) = -2J_y E_y - 2\varepsilon_0 \partial_x E_y B_z$$

Fluctuations seem to move away from the boundary
A "little" magnetic bump forms and travels towards the cavity

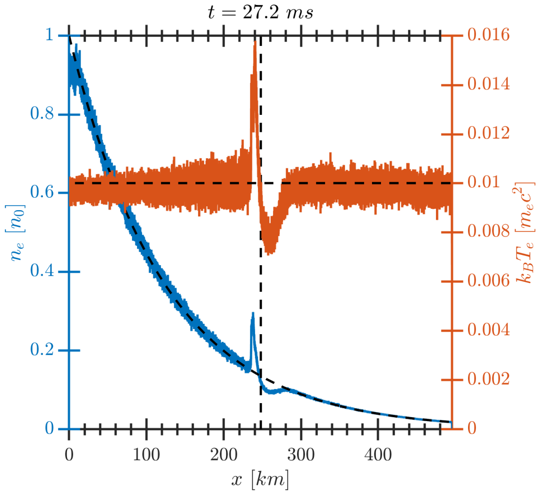
Waves





Light and plasma waves in the unmagnetised region, electron Bernstein in the magnetised region. Very tricky exercise to get them

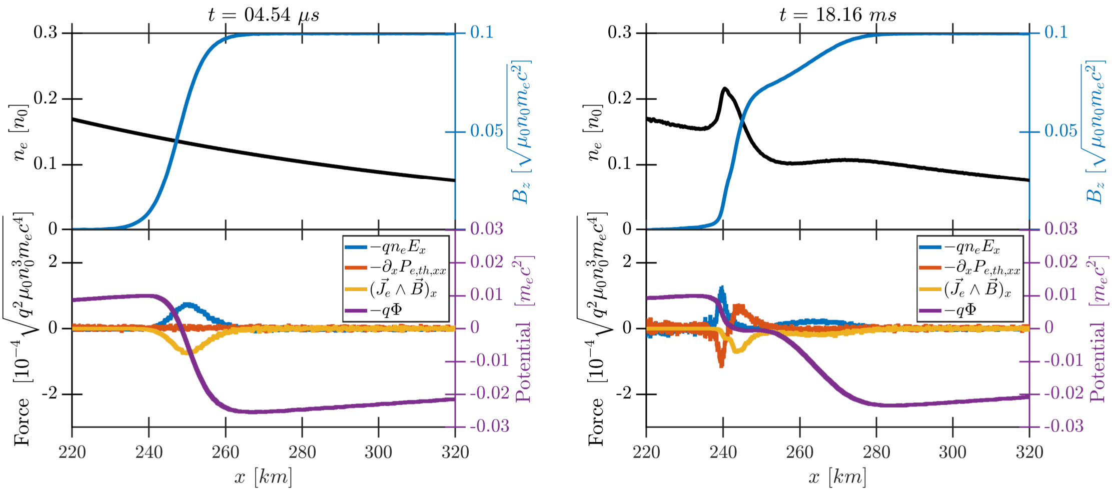
Electron pressure P_e



- plasma density piles up in front the magnetic barrier and decrease throughout.
- electron temperature follows the same trend

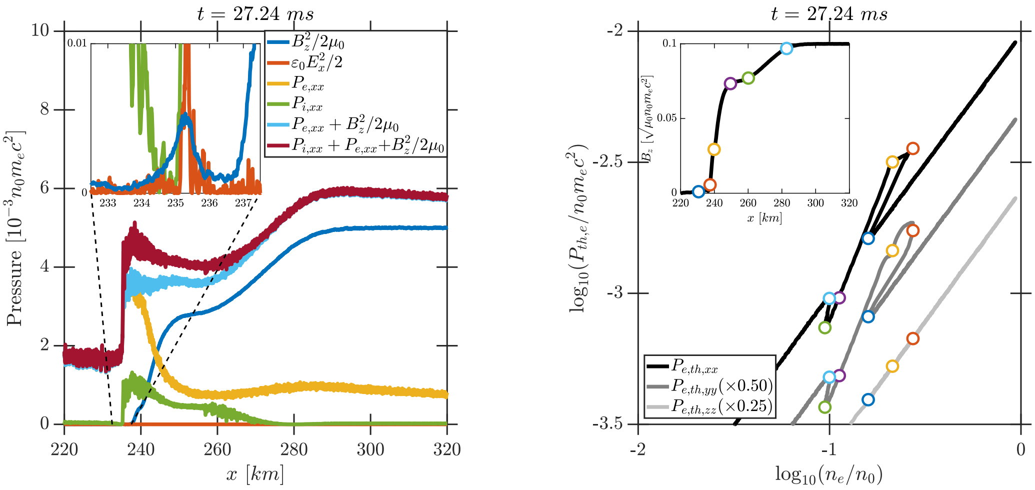
⟶ electron pressure driven by both temperature and number density

Ohm's law



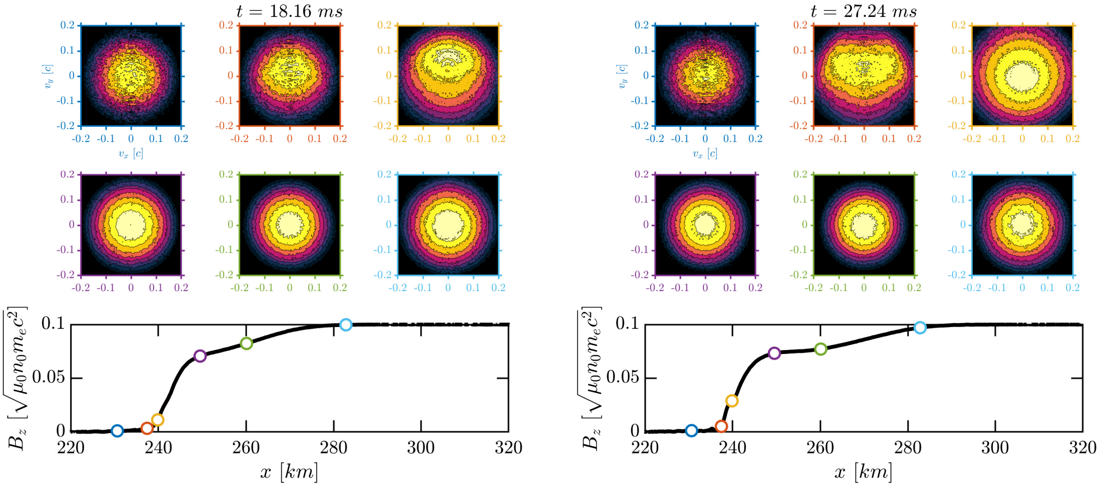
A potential barrier forms, electrons are trapped on the left by the electric field (potential of the order of $k_B T_e$) and by the magnetic field on the right $\longrightarrow$ Double layer configuration?

Pressure balance and adiabaticity



Strong pressure discontinuities but $P_e + B_z^2/2\mu_0 =$ constant over a certain region. γ varies across the boundary. P_e anisotropic

EVDF across the boundary



EVDF gyrotropic in the magnetised region but completely anisotropic at the bottom of the magnetic barrier

Agyrotropicity

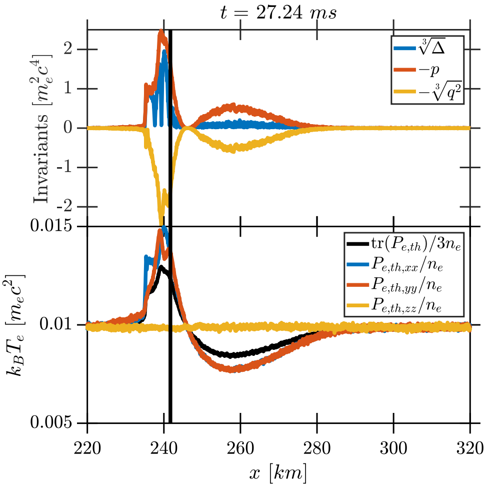


Figure: Invariants and eigenvalues of P_e

From the electron pressure tensor, I am looking for eigenvalues (using Cardano's method)

- 3 equal roots: isotropic ($\Delta = p = q = 0$)
- 2 equal, 1 different: likely gyrotropic (the eigenvector must be along B, $\Delta = 0$ but $p = q \neq 0$)
- 3 different eigenvalues: agyrotropic ($\Delta \neq 0$)

Conclusions

Take-Home messages

- First time a PIC code is used to look at the diamagnetic cavity
- $\vec{E} \approx -\nabla P_e / q n_e + J_e \times \vec{B} / q_e n_e \approx 0$: diamagnetic current at the boundary
- Agyrotropic electrons in the weak magnetic field region
- Double layer structure forming at the boundary and propagating inwards

What next?

- 2D
- Bigger simulations to run longer
- Looking at instabilities in 2D

[1]

[1] Most of the presentation is based on https://doi.org/10.1051/0004-6361/202243209