Oblique magnetic field effect on radial plasma dynamics

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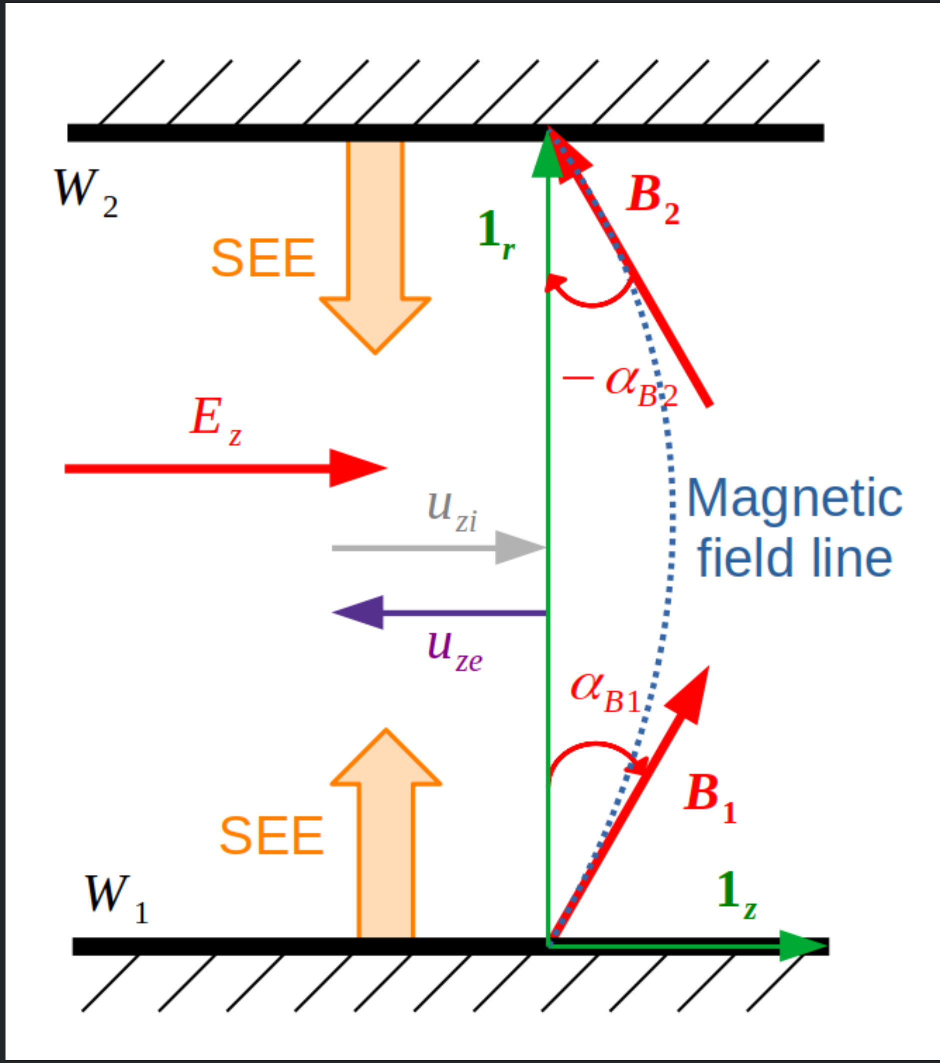
Introduction and background

- **Plasma wall interaction:** energy loss, plasma recombination, wall material erosion.
- In a HET chamber: Low collisionality + strong interaction with the walls.
  - Non-Maxwellian species VDFs.
  - Kinetic models should be used.
- Previous kinetic (PIC) studies in HET plasma discharges.
  - Magnetic field perpendicular to the walls ($B = B_r$).
    - Most works regarding plasma-wall interaction. Refs. [1-3].
    - Significant depletion of the radial electron VDF.
    - Temperature anisotrpy.
  - Oblique magnetic field.
    - Miedzik et al. Ref. [4].
    - Enhanced isotropization of electron temperature, even for a small departure from the normal incidence.
    - Questions the simplification ($B = B_r$) of many kinetic models.
- Other related studies.
  - Supersonic ions at the sheath edge
  - Magnetic presheath

The 1Dr PIC model

- Simulation sketch

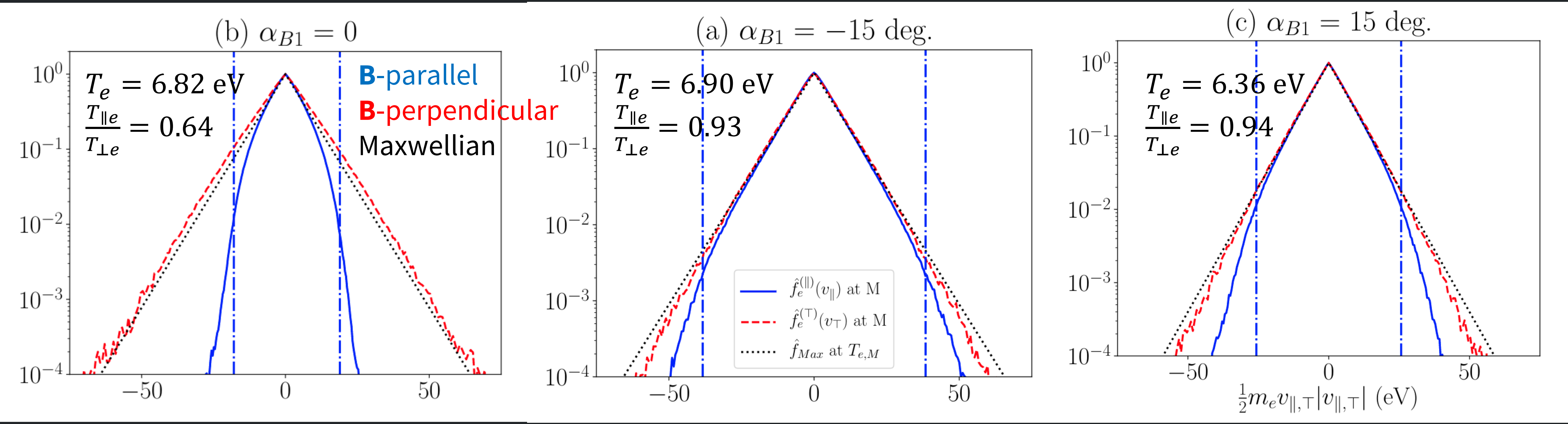


The model details can be found in Ref. [3]

- Particle populations
  - Magnetized electrons
  - Unmagnetized ions
- Neutral background
  - Uniform density and temperature
- Dielectric walls
  - Sink of electrons and ions (plasma recombination)
  - Source of secondary electrons
- Collisions
  - Coulomb: $e-e, e-i, i-i$.
  - $e-n$: elastic, excitation, ionization.
  - Allows to transfer $s \to p$.

Kinetic simulations

- Electron VDF at the mid-channel radius (M)
- Radial magnetic field
  - Highly anisotropic
  - Highly depleted VDF tails
- Oblique magnetic field
  - Significantly more isotropic
  - Largely replenished VDF tails



Dashed-dot lines: Approximate wall collection energy

Kinetic simulations

- Macroscopic magnitudes
  - Largely affected by the wall incidence angle
  - Different trends can be observed for positive and negative angles

- Electron-wall interaction parameters

$$\sigma_{rp} = \frac{\left|j_{re}^{(tw)}\right|}{j_{re,th}^{(tw)}}$$

Particle losses to the wall decrease.

REF.

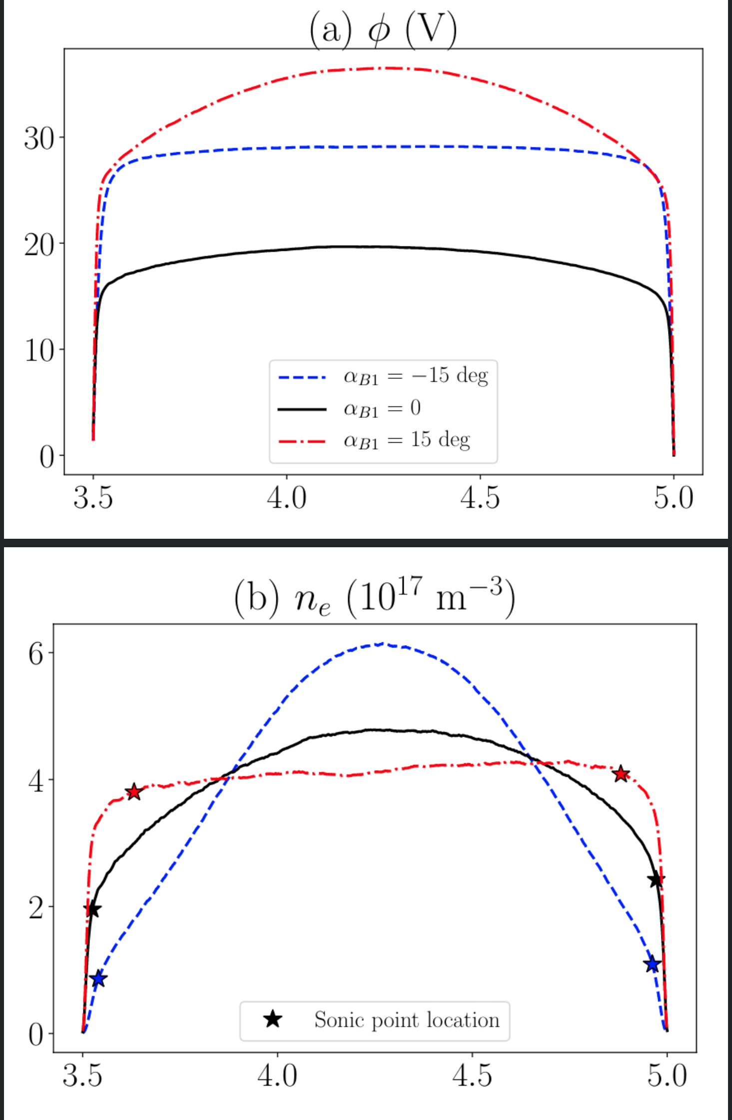
Particle losses to the wall increase.

Magetic field angle (deg.)	α_{B1}	-15	-10	-5	0	5	10	15
Current densities to walls (A/m^2)	$j_{re,1}^{(tw)}$	41	50	60	81	123	163	196
	$j_{re,2}^{(tw)}$	54	68	92	131	157	185	220
Replenishment factor $(-)$	$\sigma_{rp,1}$	0.28	0.21	0.11	0.06	0.15	0.34	0.49
	$\sigma_{rp,2}$	0.33	0.27	0.12	0.07	0.17	0.36	0.50

$$j_{re,th}^{(tw)} = e n_{e,Q} \exp\left(-\frac{\phi_{WQ}}{T_{e,Q}}\right)\sqrt{\frac{T_{e,Q}}{2\pi m_e}}$$

Maxwellian thermal flux to the wall

Replenishment factor increases significantly in scenarios with an oblique magnetic field.

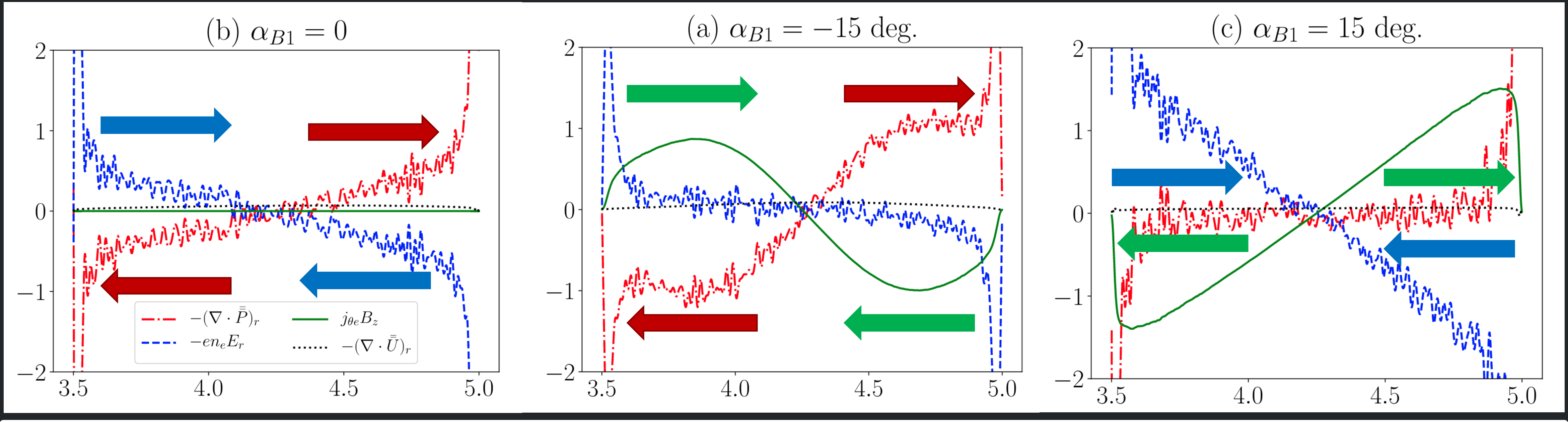


Kinetic simulations

- Radial momentum balance

$$0 \simeq -(\nabla \cdot \bar{\bar{U}})_r - (\nabla \cdot \bar{\bar{P}})_r - en_eE_r + j_{\theta e}B_z$$

- Radial Magnetic field
  - Electric and pressure forces balance each other.
  - Small inertia contribution.
  - Null magnetic force
- Negative incidence angle
  - Pressure force balances the magnetic force.
  - Small contributions from the electric force and inertia
- Positive incidence angle
  - Electric force balances the magnetic force.
  - Small contributions from the pressure force and inertia



The magnetic force confines the electron population if $\alpha_{B1} < 0$ and pushes then towards the walls if $\alpha_{B1} > 0$.

Simplified fluid model

- Equations

$$\frac{\mathrm{d}}{\mathrm{d}r}(n_e u_{ri}) = n_e \bar{\nu}_{prod},$$

$$m_i \frac{\mathrm{d}}{\mathrm{d}r}(n_e u_{ri}^2) = -e n_e \frac{\mathrm{d}\phi}{\mathrm{d}r},$$

$$0 = -T_e \frac{\mathrm{d}n_e}{\mathrm{d}r} + e n_e \frac{\mathrm{d}\phi}{\mathrm{d}r} - e n_e E_z \tan(\alpha_B),$$

- Continuity
- Momentum (i)
- Momentum (e)

- Solution in non-dimensional form
  - Non-dimensional variables

$$(1 - \hat{u}_{ri}^2) \frac{\mathrm{d}\hat{u}_{ri}}{\mathrm{d}\zeta} = \hat{\nu}_{prod}(1 + \hat{u}_{ri}^2) - 2F\hat{u}_{ri}\zeta,$$

- B.C. (1st order ODE)

$$(\zeta = 0) \quad \hat{u}_{ri} = 0$$

$$\hat{u}_{ri} = \frac{u_{ri}}{c_s},$$

- Dependent variable

$$\zeta = \frac{r - r_M}{d},$$

- Independent variable

$$\hat{\nu}_{prod} = \bar{\nu}_{prod} \frac{d}{c_s},$$

- Free parameter

$$F = \frac{e E_z}{T_e} \frac{d}{2} \tan \alpha_{B1},$$

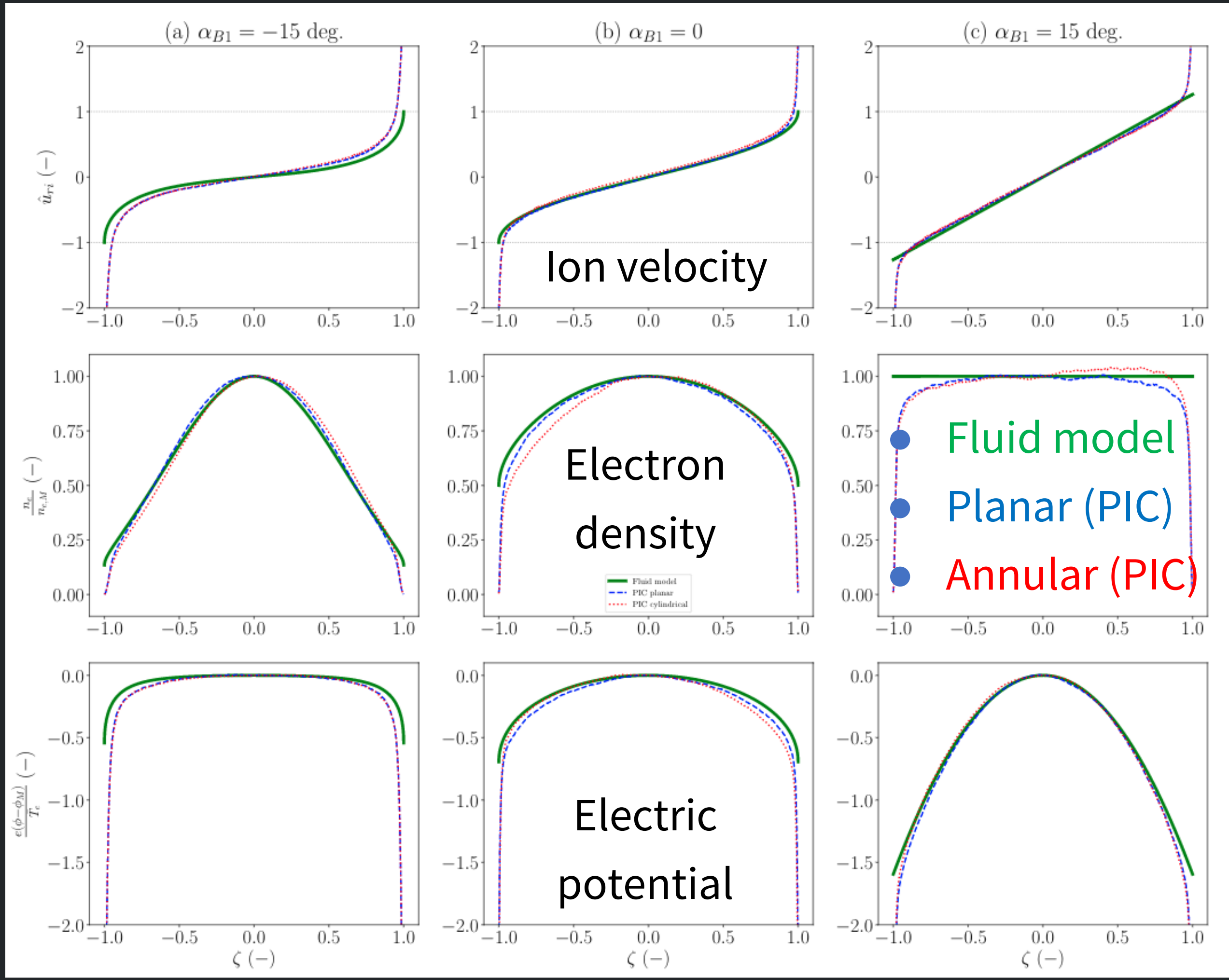
- Known

- Main model assumptions
  - Planar ($1/r \sim 0$)
  - Quasineutral ($n_e = n_i$)
  - Zero Debye length limit
  - Massless electrons
  - Negligible ion pressure
  - Collisionless (for momentum eq.)
  - Uniform and isotropic electron temperature
  - Constant production frequency

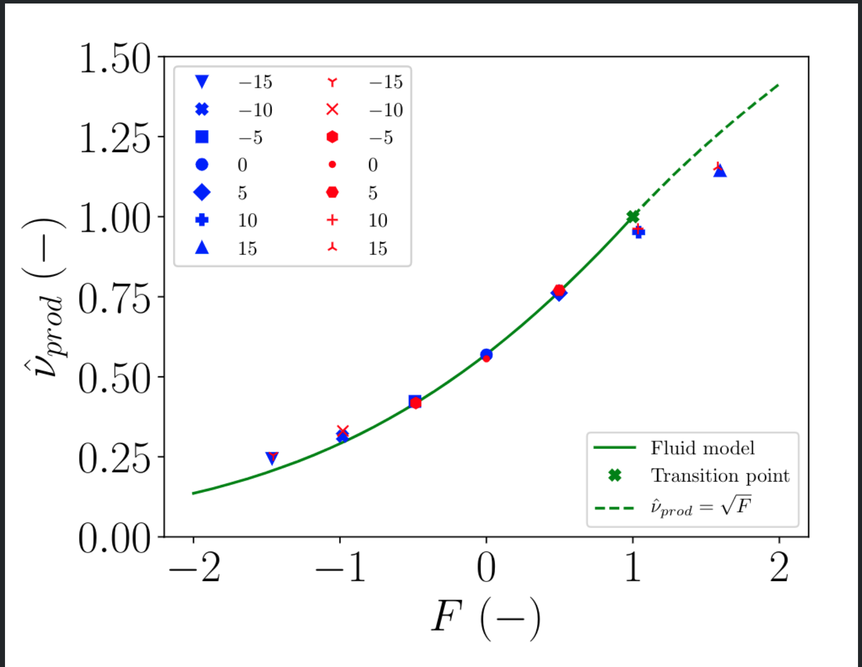
- Two different regimes exist depending on the value of F
  I. Sonic flow at the sheath edge ($F < 1$)
  II. Supersonic ion flow ($F > 1$)

Simplified fluid model

- Comparison of radial profiles



- Parametric relation



Good agreement between PIC and fluid.
Quasineutral magnetic presheath?

Conclusion and future work

- As in Ref. [4], simulations with an oblique magnetic field lead to a significant isotropization of the electron population.
- The oblique magnetic field has a strong influence on macroscopic plasma magnitudes.
- Depending on incidence angle, the radial magnetic force can promote plasma losses to the walls or act as shielding.
- A simplified fluid model of the discharge has been proposed and validated against PIC solutions.
- For positive incidence angles, the sonic point moves inwards the channel and ions may become supersonic at the quasineutral region.
- 2D(r-z) PIC models currently in development will confirm or modify the conclusions extracted from this analysis.

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BACKUP SLIDES

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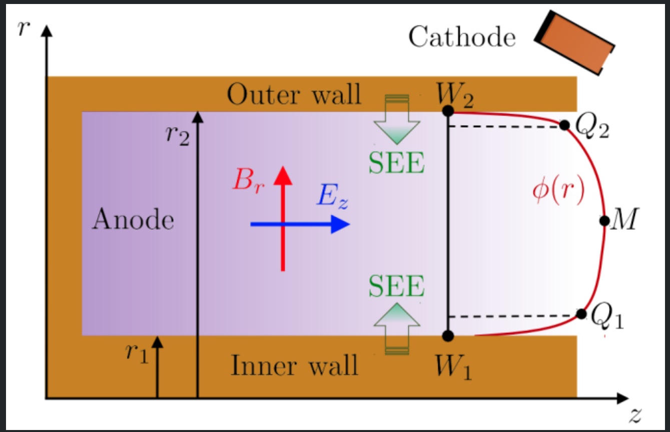
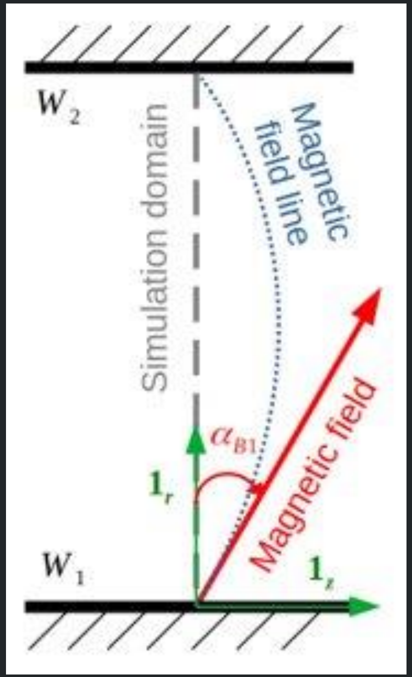
The 1Dr PIC model

- HET sketch



- Fields acting on the plasma
  - Constant E_z
  - $E_r \rightarrow$ 1Dr Poisson equation.
  - Prescribed $\boldsymbol{B}$-field
  - Wall incidence angle α_{B1}
  - Symmetric configurations $\alpha_{B1} = -\alpha_{B2}$
  - $\bar{B} = constant$

- B-field sketch



The model details can be found in Ref. [3]

- Magnetized electrons
  - $\boldsymbol{E} \times \boldsymbol{B}$ azimuthal drift
  - $e = p + s$
- Unmagnetized singly charged ions
  - Only affected by E_r
  - Generated with u_{zi}

Initially Maxwellian
$n_e = n_i$
$T_e = 10\ eV, T_i = 1\ eV$

- Neutral background
  - Uniform $n_n(t)$ and T_n
- ICD: ionization balances wall losses at stationary conditions

- Collisions
  - Coulomb: $e - e, e - i, i - i$.
  - $e - n$: elastic, excitation, ionization.
  - Allows to transfer s $\rightarrow p$.

- Dielectric walls
  - Sink of electrons and ions (plasma recombination)
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Kinetic simulations

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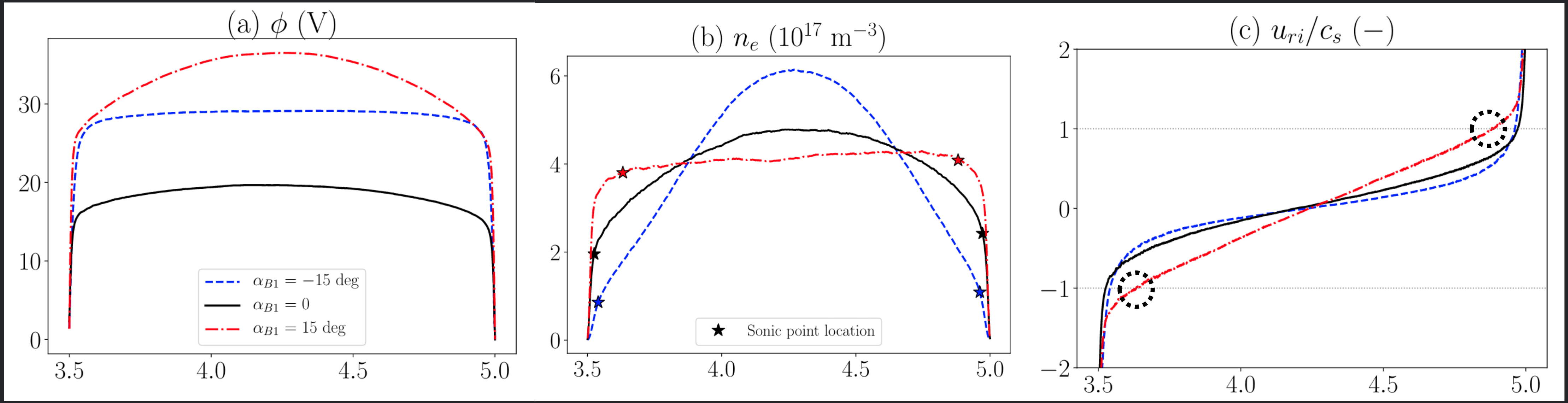

Particle losses to the wall decrease ← REF. → Particle losses to the wall increase

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Current densities to walls (A/m^2)	$j_{re,1}^{(tw)}$	41	50	60	81	123	163	196
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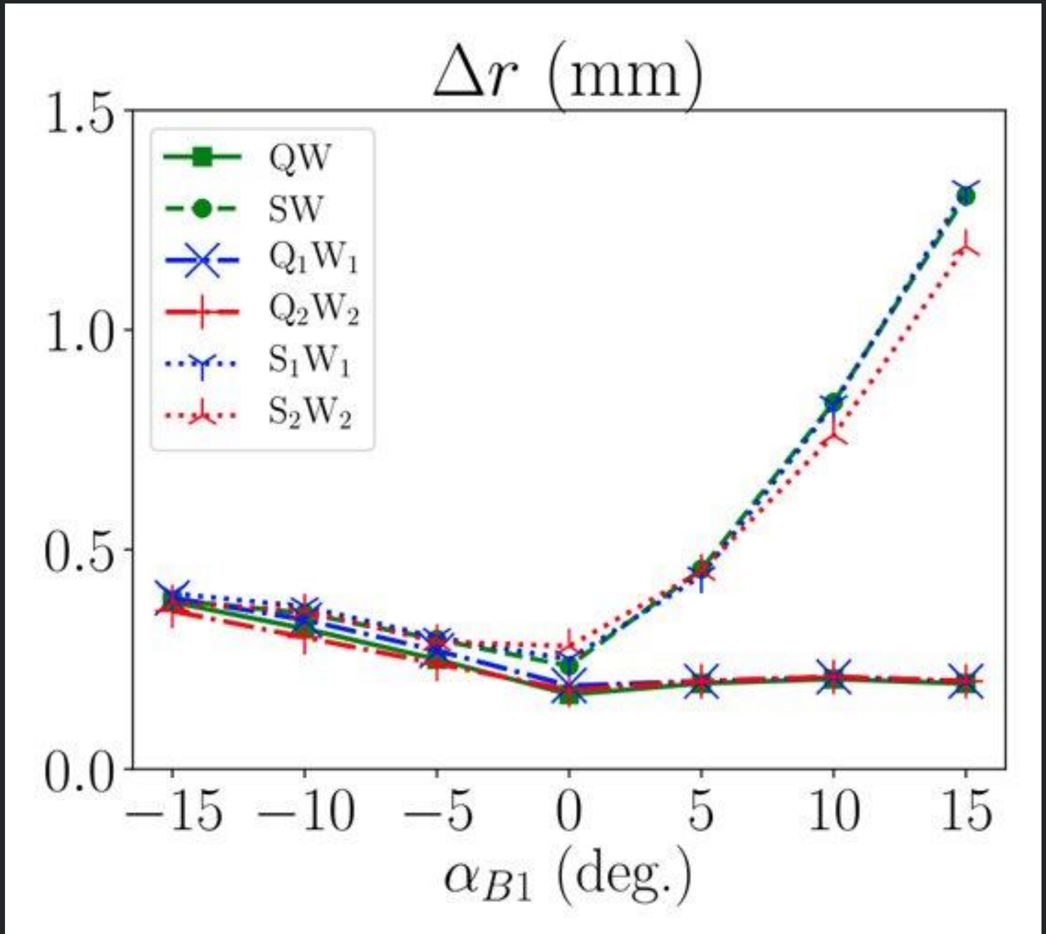
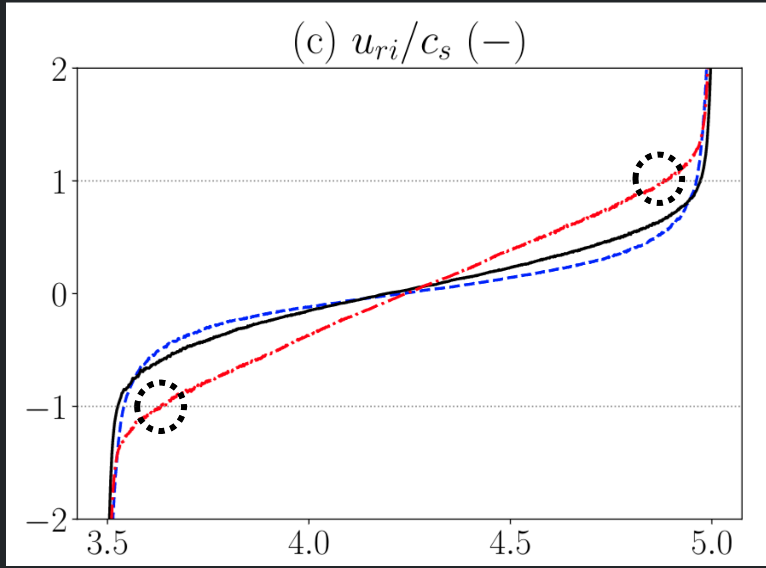
Further results

- Ion sonic point location (PIC simulations)

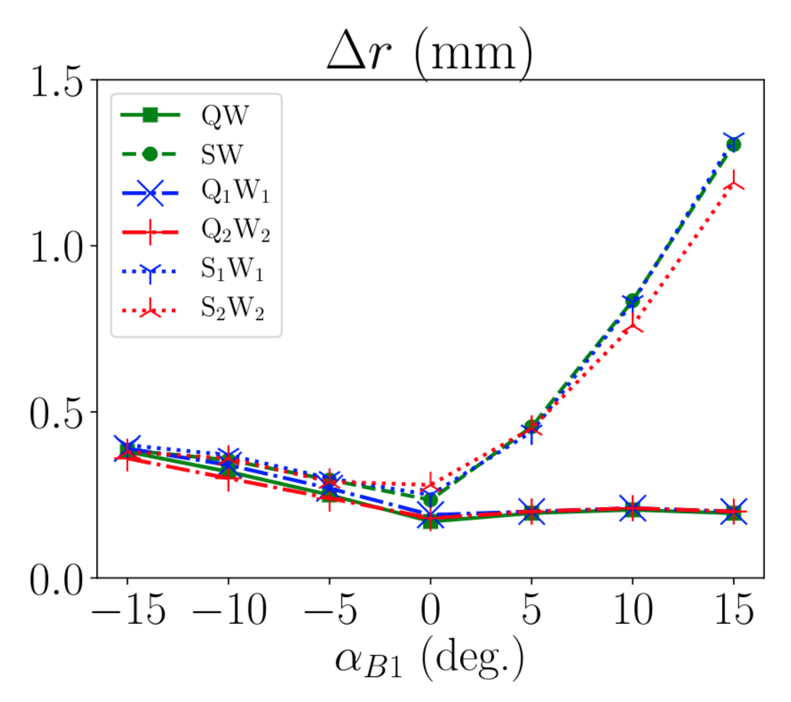




- Sonic point moves inwards the quasineutral region.
- This behavior is also captured by the fluid model (Regime II).

Further discussion

- Sonic point and sheath edge locations diverge for positive values of α_{B1} in PIC simulations. Such shift of the sonic point inwards the quasineutral region is also predicted by the fluid model (Regime II).



- For higher temperatures (as it is the case when anomalous collisions are included in the simulation) the oblique magnetic field has a smaller effect on the plasma response ($F \propto \tan(\alpha_{B1})/T_e$).

- Secondary electrons have a marginal role in all the cases considered in this work. However, in discharges dominated by secondary electrons (beyond the charge saturation limit) this behavior may change.