Modeling of plasma parallel transport in the Material Plasma Exposure eXperiment (MPEX) during radio-frequency heated discharges

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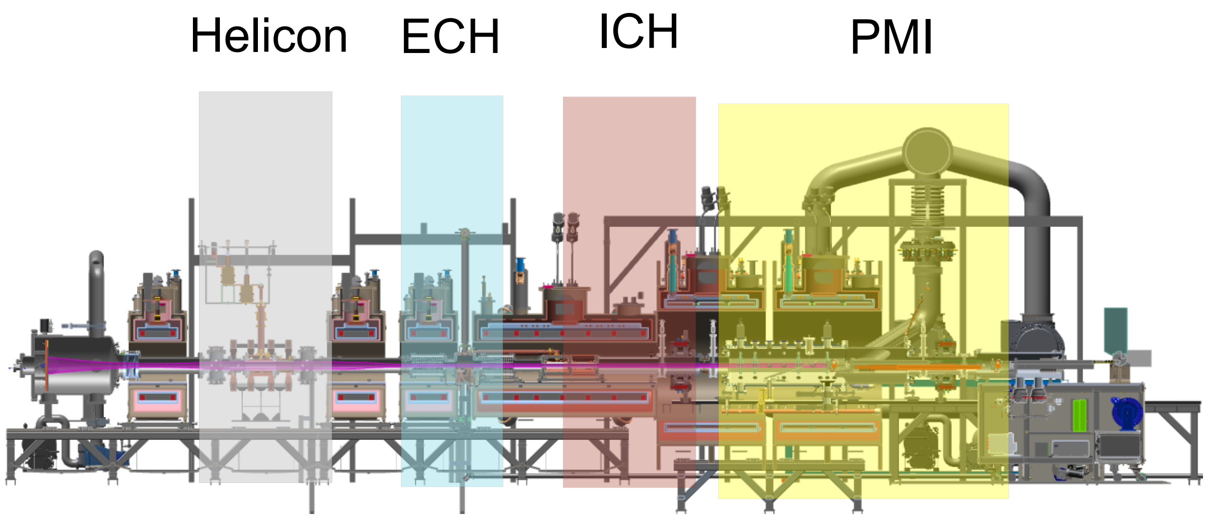
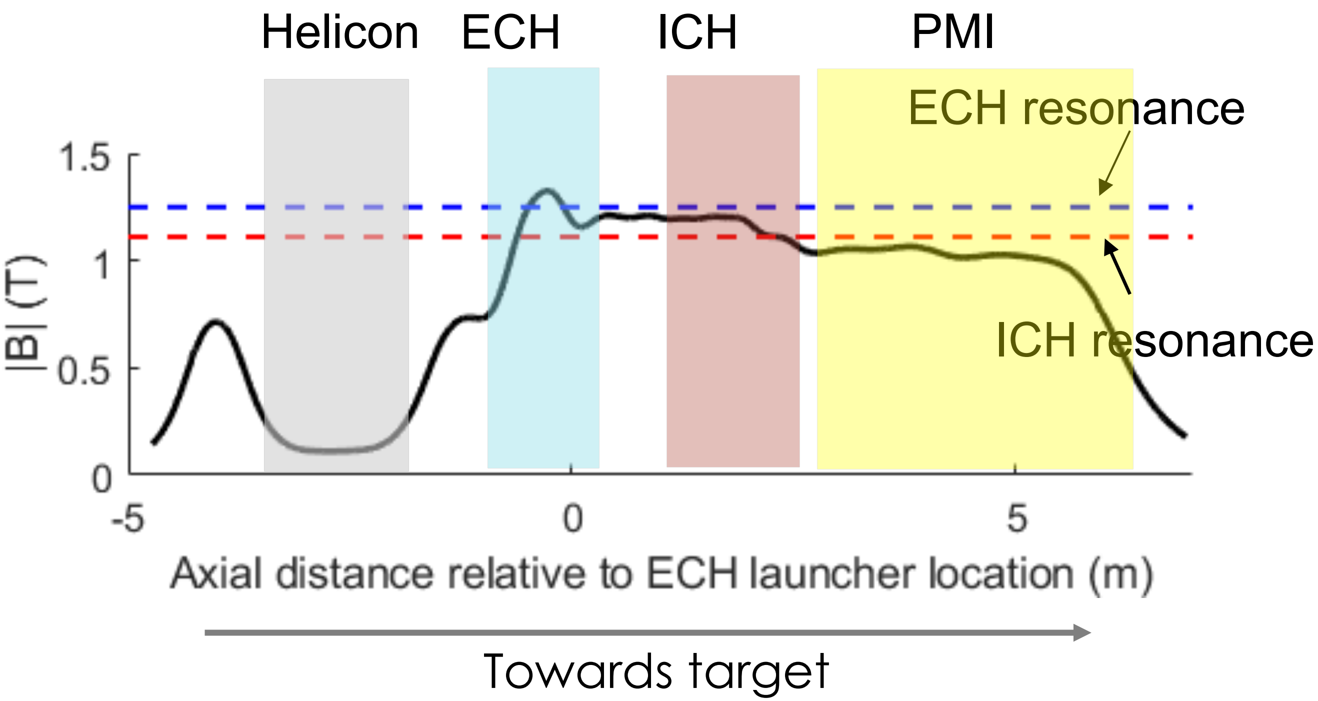
MPEX will study PMI at future fusion reactor relevant plasma conditions

- **Material Plasma Exposure eXperiemnt (MPEX)** will enable PMI studies at future fusion reactor relevant plasma conditions.
- Targets exposure time in MPEX up to ~ 2 weeks and ion fluence $\sim 10^{31}/m^2$
- 2 weeks of exposure time for any material target in MPEX ~ lifetime exposure in MCF devices
- A prototype of MPEX- 'Proto-MPEX' is conducted R&D related to heating schemes for MPEX
- **"Density drop near the target"** observed in Proto-MPEX experiments during ICH discharges
- **"PICOS++- a quasi-neutral PIC code for open systems"** is developed and applied to understand the "density-drop" behavior and to find possible solution.





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MPEX/Proto-MPEX plasma can not be modelled by existing fluid and fully kinetic codes, needs Hybrid PIC treatment !!

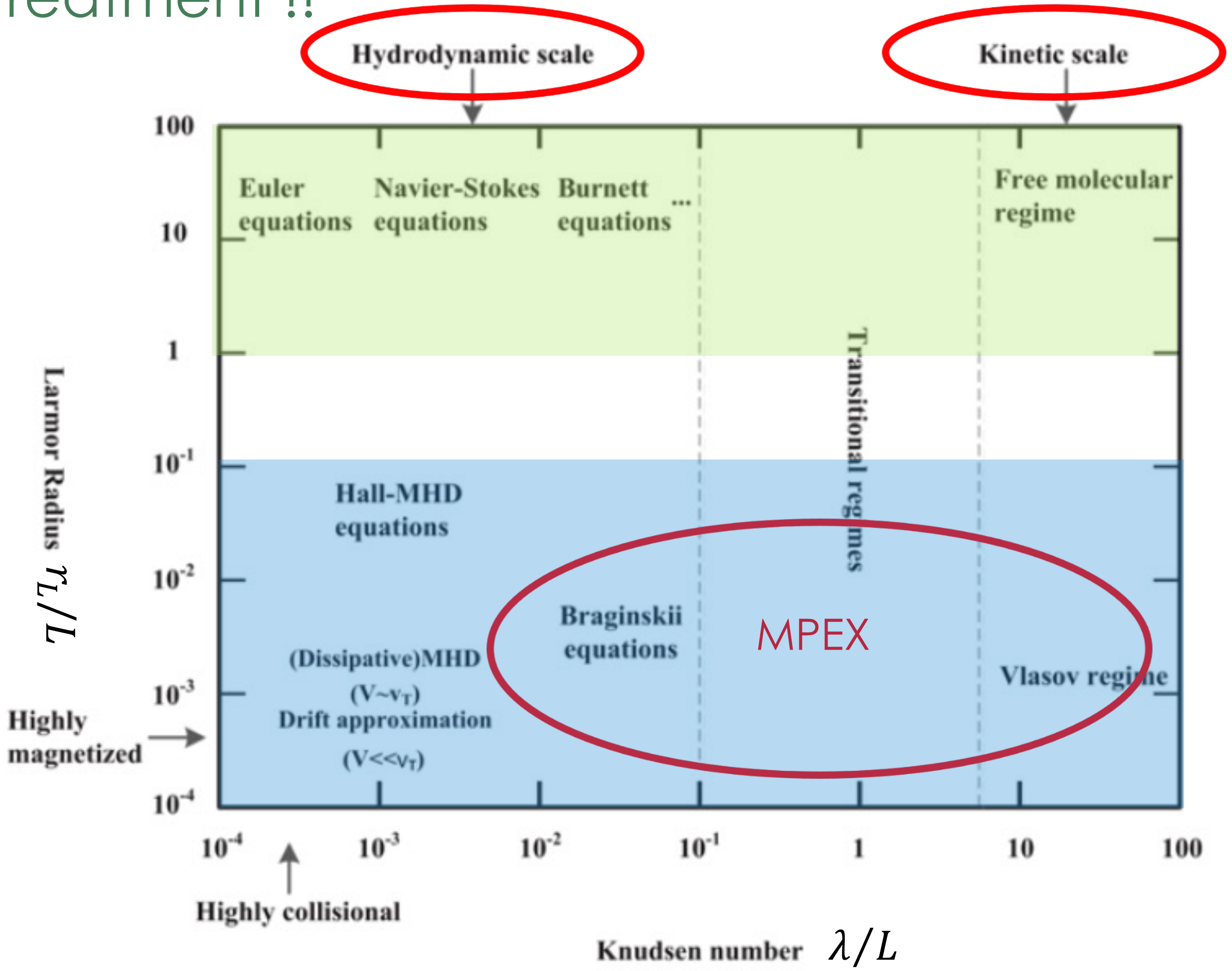
- MPEX plasma conditions:
  - Primary heating: **Helicon source** for plasma production
  - Auxiliary heating schemes:
    - **Electron cyclotron heating** with 70 and 105 GHz EBW
    - **Ion cyclotron heating** with 4-9 MHz
  - Targets will be exposed with ion fluence $\sim 10^{31}/m^2$ up to ~ 2 weeks

- During ECH/ICH, both thermal and non-thermal plasma components are produced.

- **Mixed collisionality!!**; Can not be modelled with available Fluid codes like SOLPS and bounced averaged kinetic codes like CQL3D.

- Adopted a "hybrid" Particle-In-Cell approach to model parallel plasma transport in MPEX/Proto-MPEX

  - **Hybrid**: Kinetic ions and fluid electrons



Kumar et. Nucl. Fusion (2023), 63, 036004; Kumar et. al, PPCF (2022), 64, 035005

Computational framework: PICOS++

- PICOS++: Particle-In-Cell for Open Systems
  - MPI + open MP architecture
  - Runs in HPC environment

- Solve the Boltzmann equation in 1D-2V space
  - Approximations:
    - Electrostatic $\boldsymbol{E} = -\nabla\phi$
    - Guiding center $\mu = \frac{mv_\perp^2}{2B}$
    - No radial transport
    - No neutral dynamics
  - Operators:
    - Coulomb collisions (Fokker-Planck)
    - Quasilinear RF heating
    - Volumetric particle sources (NBI/Isotropic)
  - Multiple ion species

- PIC approach
  - Klimontovich distribution function
    - Magnetic compression

⬇

1D-2V Reduced Klimontovich PDF

$$f_K(x, v_\parallel, v_\perp, t) = \sum_{i=1}^{N_R} \frac{\delta\left(x - x_i(t)\right)}{A(x_i)} \delta(v_\parallel - v_{\parallel i}(t))\delta(v_\perp - v_{\perp i}(t))$$

Equations of motion

$$\frac{dx_i}{dt} = v_{\parallel i}$$

$$m\frac{dv_{\parallel i}}{dt} = -\mu_i \frac{dB_i}{dx} - qE_{\parallel i}$$

$$\frac{d\mu_i}{dt} = 0 \quad \text{where} \quad \mu_i = \frac{mv_{\perp i}^2}{2B_i}$$

Electric field

$$E_\parallel = -\frac{1}{en_e}\frac{dP_{e\parallel}}{dx}$$

Boundary conditions:
- No boundary conditions for field
- Absorbing boundary conditions for particles
- Flow at the boundary is forced sonic for $M < 1$ and no BC for $M \geq 1$

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Coulomb collisions in Fokker-Planck Framework

- Monte-Carlo operator based on Kuo-Petravic and Boozer 1998 (*Kuo and Boozer Physics of Fluids 1998*)

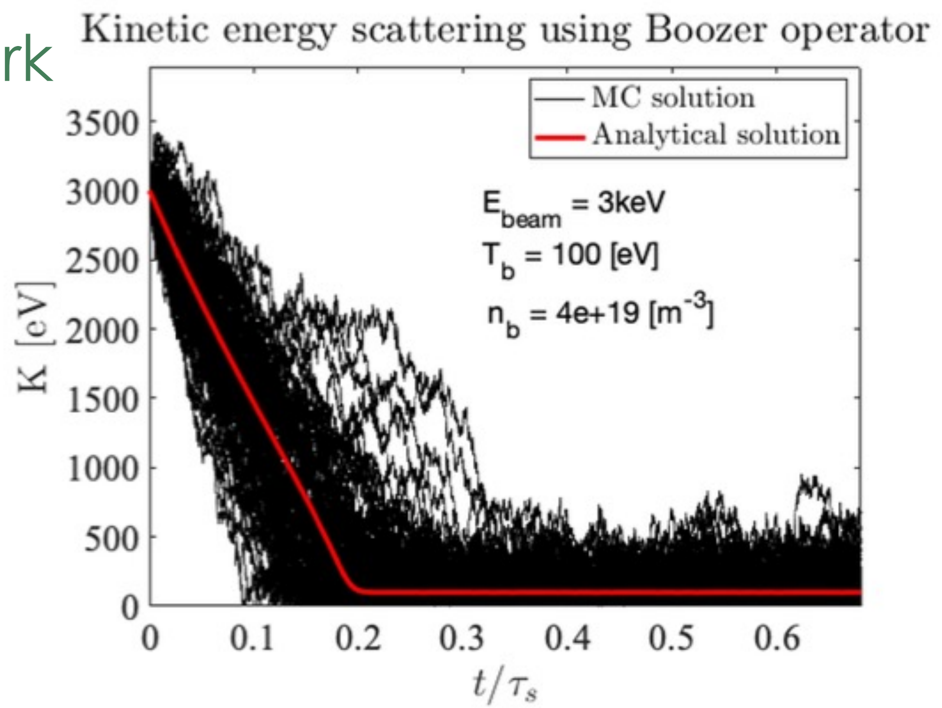
Energy scattering:

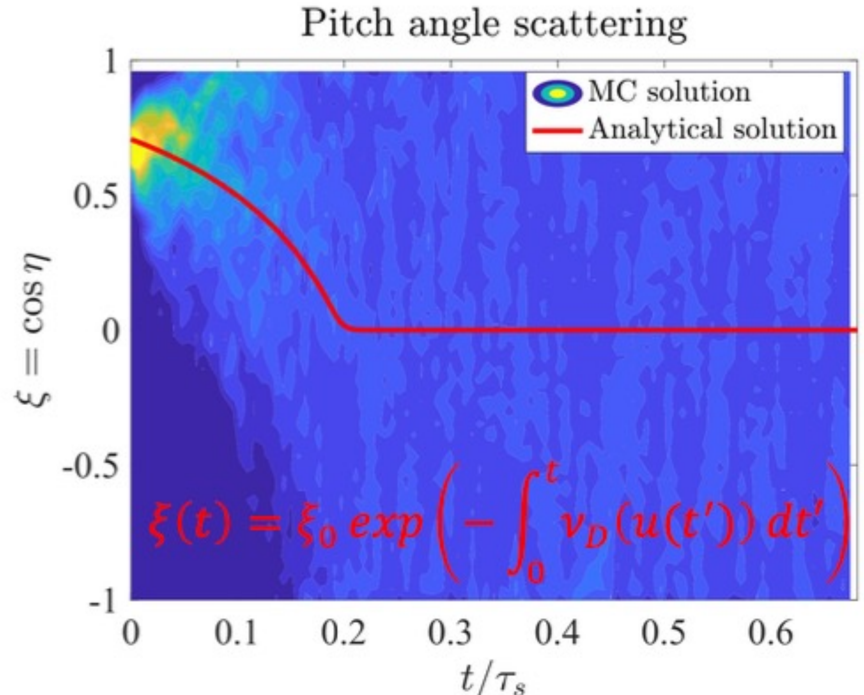
$$E_n = E_0 - (2\nu_E\tau)\left[E_0 - \left(\frac{3}{2} + \frac{E}{\nu_E}\frac{d\nu_E}{dE}T\right)\right] \pm 2[TE_0(\nu_E\tau)]^{1/2} \ldots (1)$$

Pitch angle scattering:

$$\xi_{n+1} = \xi_n\,(1 - \nu_D(v)\Delta t) \pm ([1-\xi_n^2]\nu_D(v)\Delta t)^{1/2} \ldots (2)$$

- Use moments of particle PDF to produce background conditions for FP collision operator
- FP operator is subcycled within the simulation time interval $\Delta t = N\delta t$ to satisfy the Monte-Carlo condition $\nu_D\delta t \ll 1$ and $\nu_E\delta t \ll 1$.
- This MC based FP operator is benchmarked with analytical solutions for Energy and pitch angle scattering in MATLAB.





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Implementation of Quasilinear RF Heating Operator

- RF cyclotron heating operator[1],

$$\Delta E_i = \Delta E_i^{RF}\left(1+\frac{k_\parallel v_{\parallel i}}{n\Omega_i}\right) + R_m\left(1+\frac{k_\parallel v_{\parallel i}}{n\Omega_i}\right)\sqrt{2E_{\perp i}\Delta E_i^{RF}} \quad (1)$$

- The mean change of KE for ions (+)/electrons(-),

$$\Delta E_i^{RF} = \left(\frac{e}{2m_a}\right)\left|E_\pm\right|^2 J_{n-1}^2\,(k_\perp r_{Li})\tau_i^2 \quad (2)$$

- Total RF power,

$$\dot{E}_3 = \frac{\alpha}{\Delta t}\sum_i^{N_C} a_i f_{3i}\left(\frac{e}{2m_a}\right)\left|E_\pm\right|^2 J_{n-1}^2\,(k_\perp r_{Li})\tau_i^2\left(1+\frac{k_\parallel v_{\parallel i}}{n\Omega_i}\right) \quad (3)$$

$$\alpha = \frac{N_R}{N_{SP}}$$

- Total RF power per unit E-field squared,

$$\dot{\hat{E}}_3 = \frac{\alpha}{\Delta t}\sum_i^{N_C} a_i f_{3i}\Delta\hat{E}_{3i} \quad (4)$$

$$\left|E_\pm\right|^2 = \frac{P_{RF}}{\dot{\hat{E}}_3} \quad (6)$$

$$\Delta\hat{E}_{3i} = \left(\frac{e}{2m_a}\right)J_{n-1}^2\,(k_\perp r_{Li})\tau_i^2\left(1+\frac{k_\parallel v_{\parallel i}}{n\Omega_i}\right) \quad (5)$$

Electric field is assumed to be constant for all particles in resonance

- Procedure to calculate RF kick at each time step:

  1. Check resonance number : $\omega_{RF} = n\Omega_i + k_\parallel v_{\parallel i}$
  2. Flag each particles crossing resonance
  3. Calculate the Bessel term, RF interaction time and doppler term using the particle, position, energy, pitch angle
  4. Calculate wave electric field based on inputs from step 2 and 3
  5. Apply Monte-Carlo RF heating operator using the electric field calculated from step 4

[1] Kumar et. Nucl. Fusion (2023), 63, 03600

PICOS++ modeling replicates the Proto-MPEX Helicon and Helicon+ICH expts.

Validation with Helicon only Proto-MPEX expt.

- Experiments on mirror ratio scan for Proto-MPEX helicon only case[N. Kafle et. al., 2020]
- PICOS++ reproduced the density measurements at the target and at the source.

Validation with Helicon+ICH only Proto-MPEX expt.

- PICOS++ modeling qualitatively matches with the experiments.
- "Density-drop" at the target during ICH, saturates for higher ICH power!!

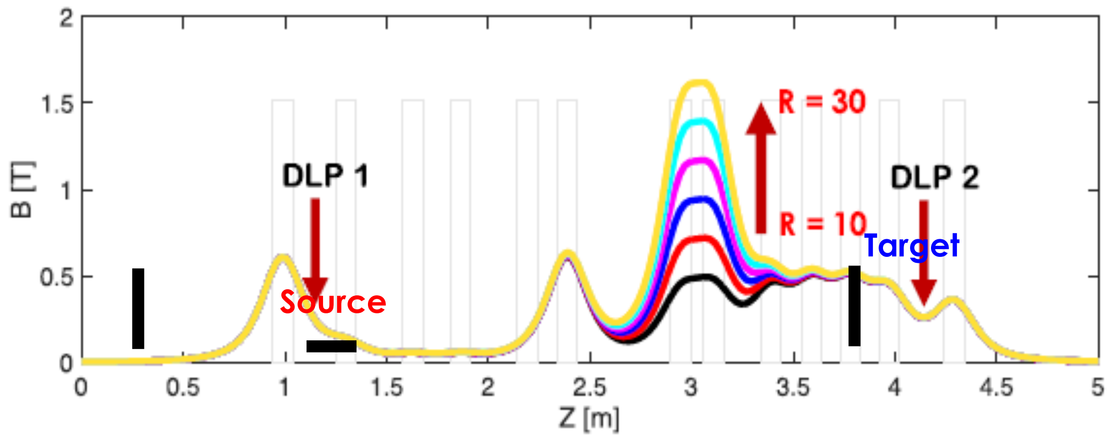
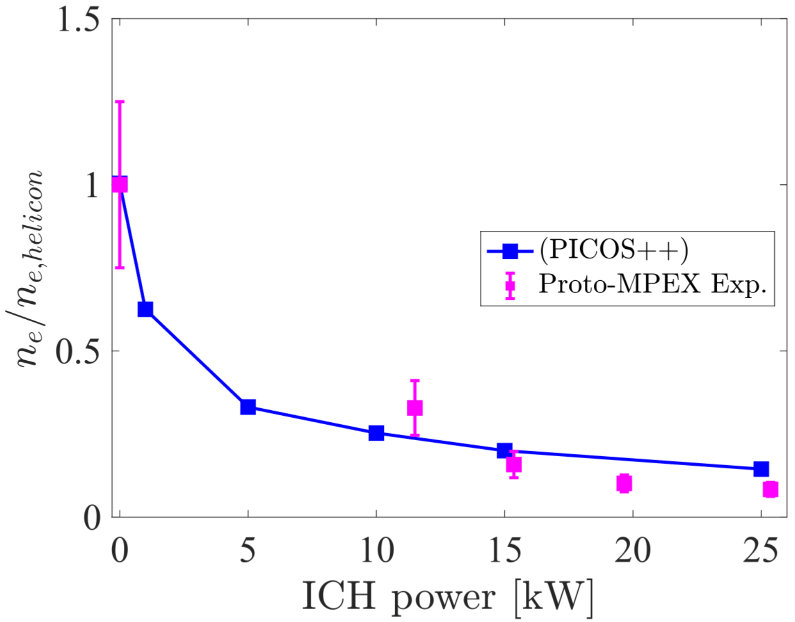
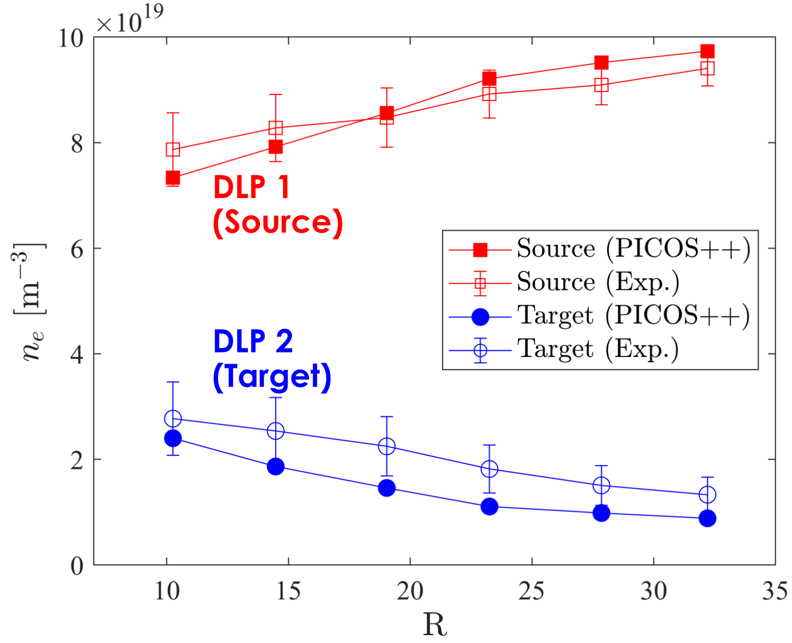


Fig. 3. Axial magnetic field indicating the location where the B scan was occurring. DLPs 1 and 2 measured n_e near the source and the target.





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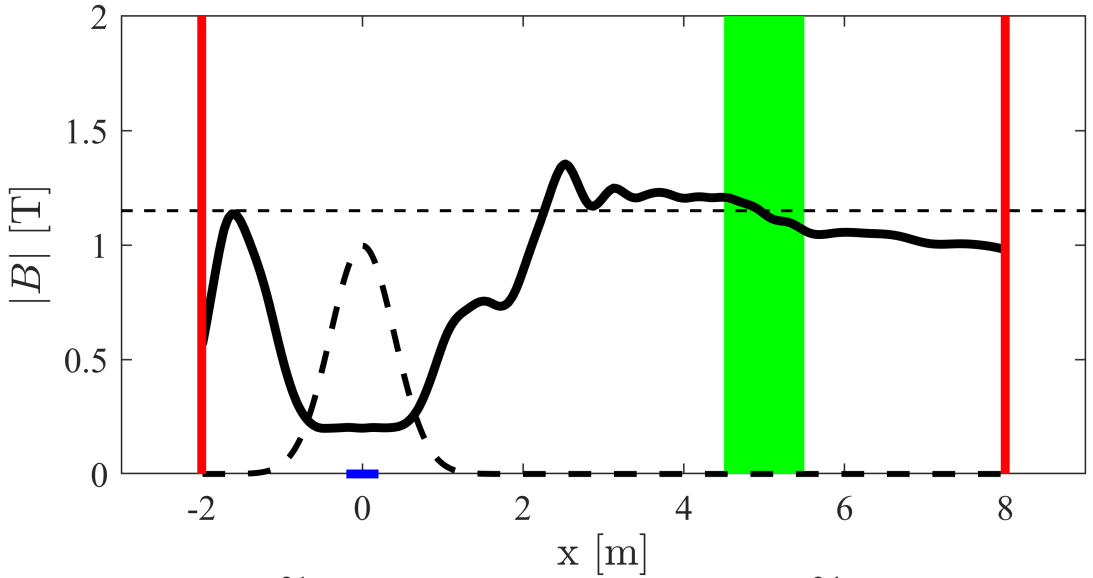
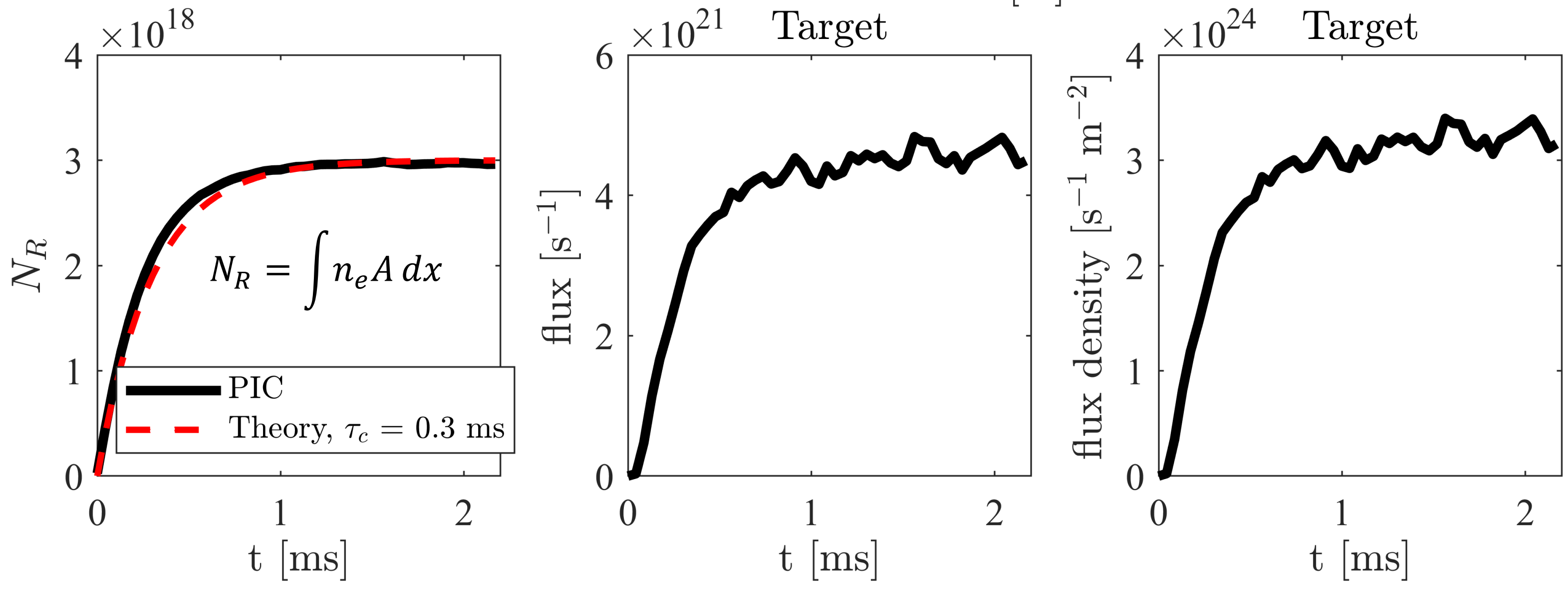
PICOS++ modelling of MPEX

MPEX transport modelling: Helicon only

- Realistic MPEX geometry;
  - B-field different than Proto-MPEX
  - MPEX~10m vs Proto-MPEX~5m
- Plasma fueling rate based on data extrapolated from Proto-MPEX
  - G = 1×10^{22} [s^{-1}]
  - T_e = 15 eV
- Reaches steady state consistent with theoretical confinement time

$$\tau_{confinement} = \frac{RL}{2C_s} \sim 0.3ms$$





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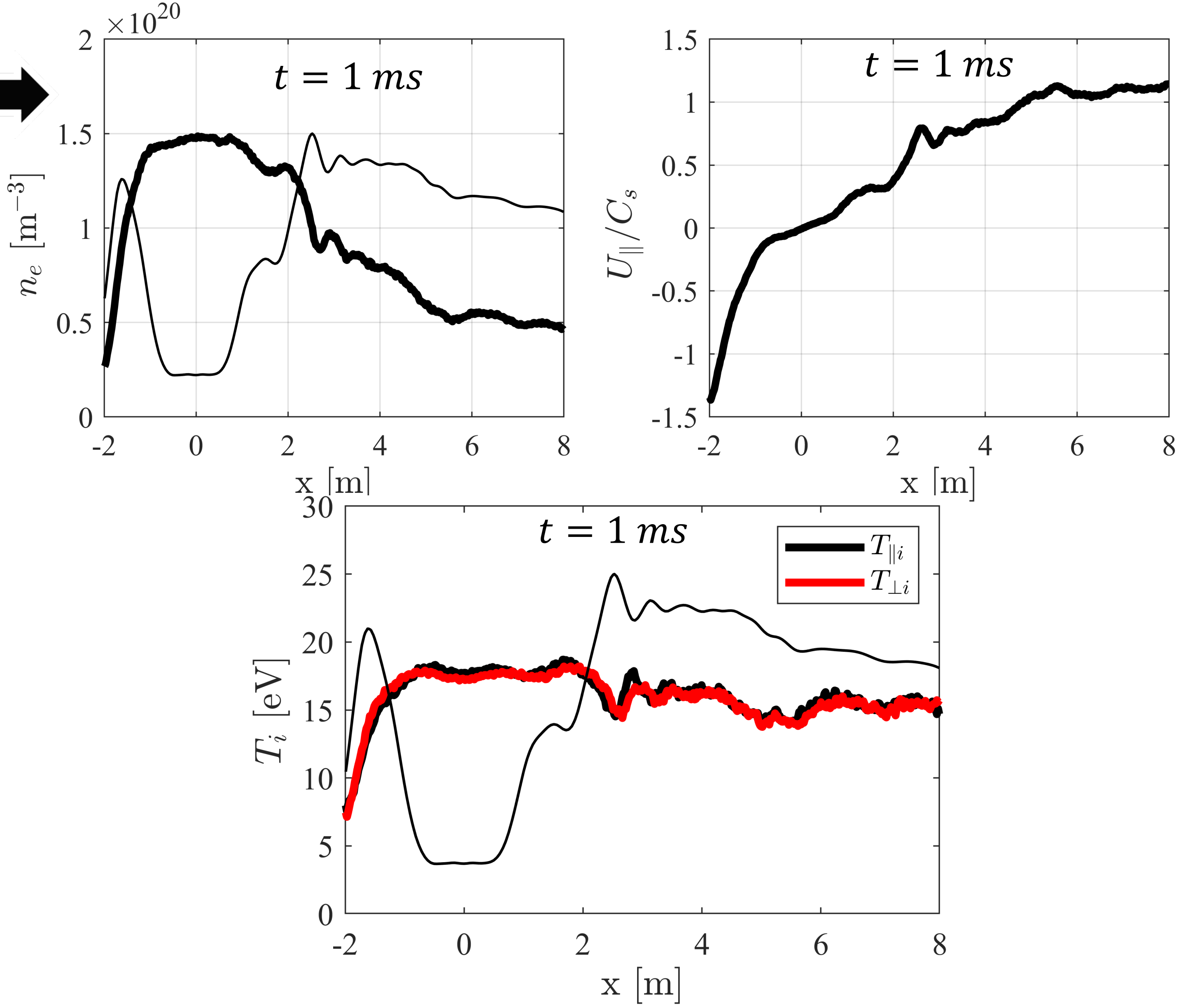
MPEX transport modelling: Helicon only

- Steady state plasma profiles for helicon only MPEX case
- Accumulation of density at the source location because of mirror confinement in collisional plasma.
- Isotropic temperature profiles with small deviations near large B-field gradients.
- Coulomb collisions are strong enough to fully equilibrate the helicon only Proto-MPEX plasma.



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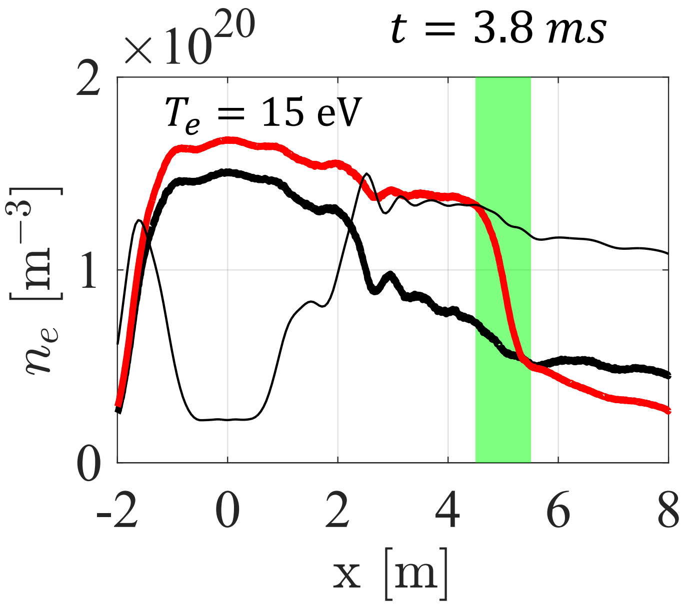
RF leads to strong modification of plasma density and flow in MPEX

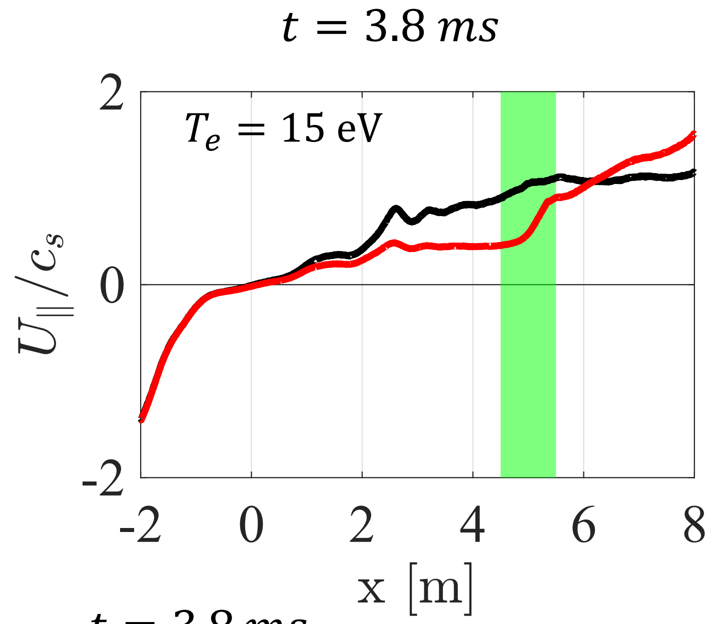
- **Applying 100 kW of absorbed ICH power at 8.7 MHz**

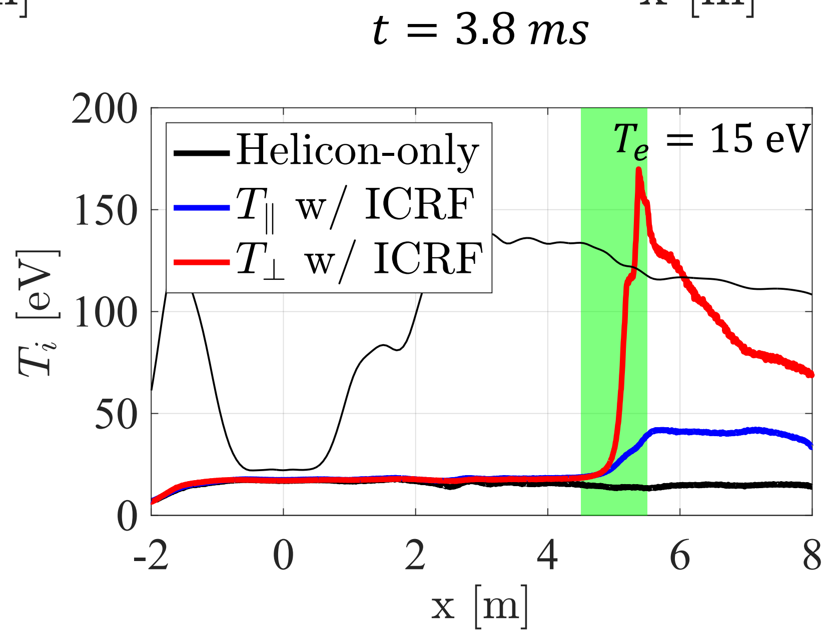
- Observations:
  - RF heating leads to strong modification of plasma density and flow
  - Strong perp. heating
  - Parallel heating is mediated by collisional relaxation

- RF heating reduces parallel transport to target

- Does it scale with RF power?
  - ✓ Density at the target keeps decreasing up to 100kW and saturates beyond that.







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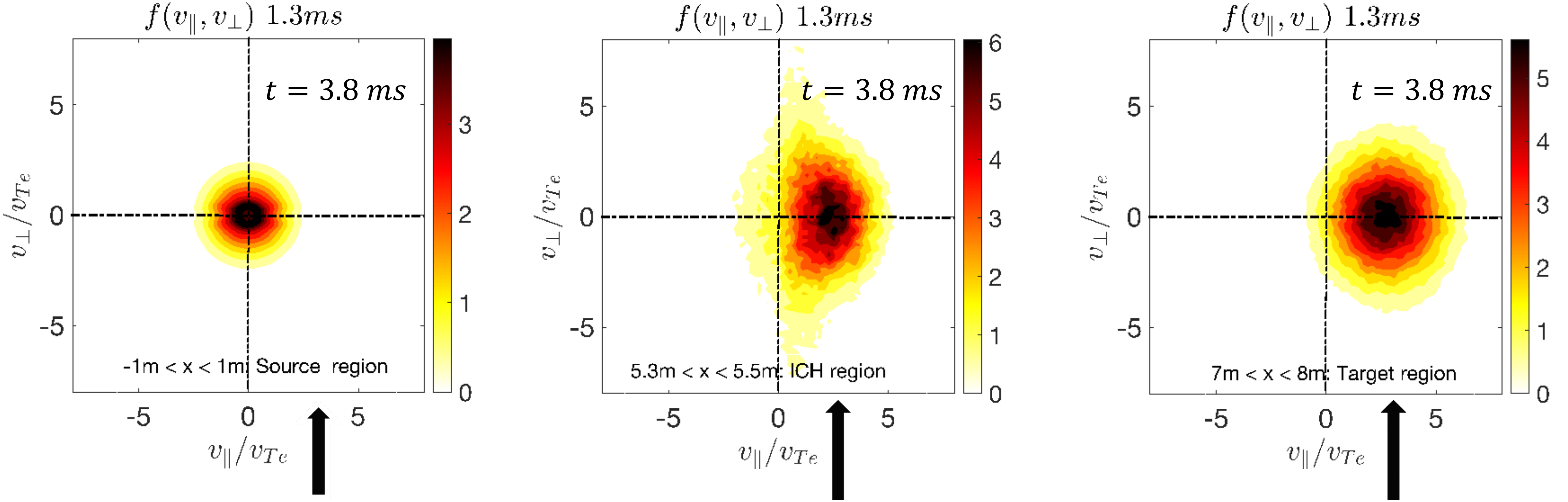
Strong parallel transport leads to two temperature distributions at the target



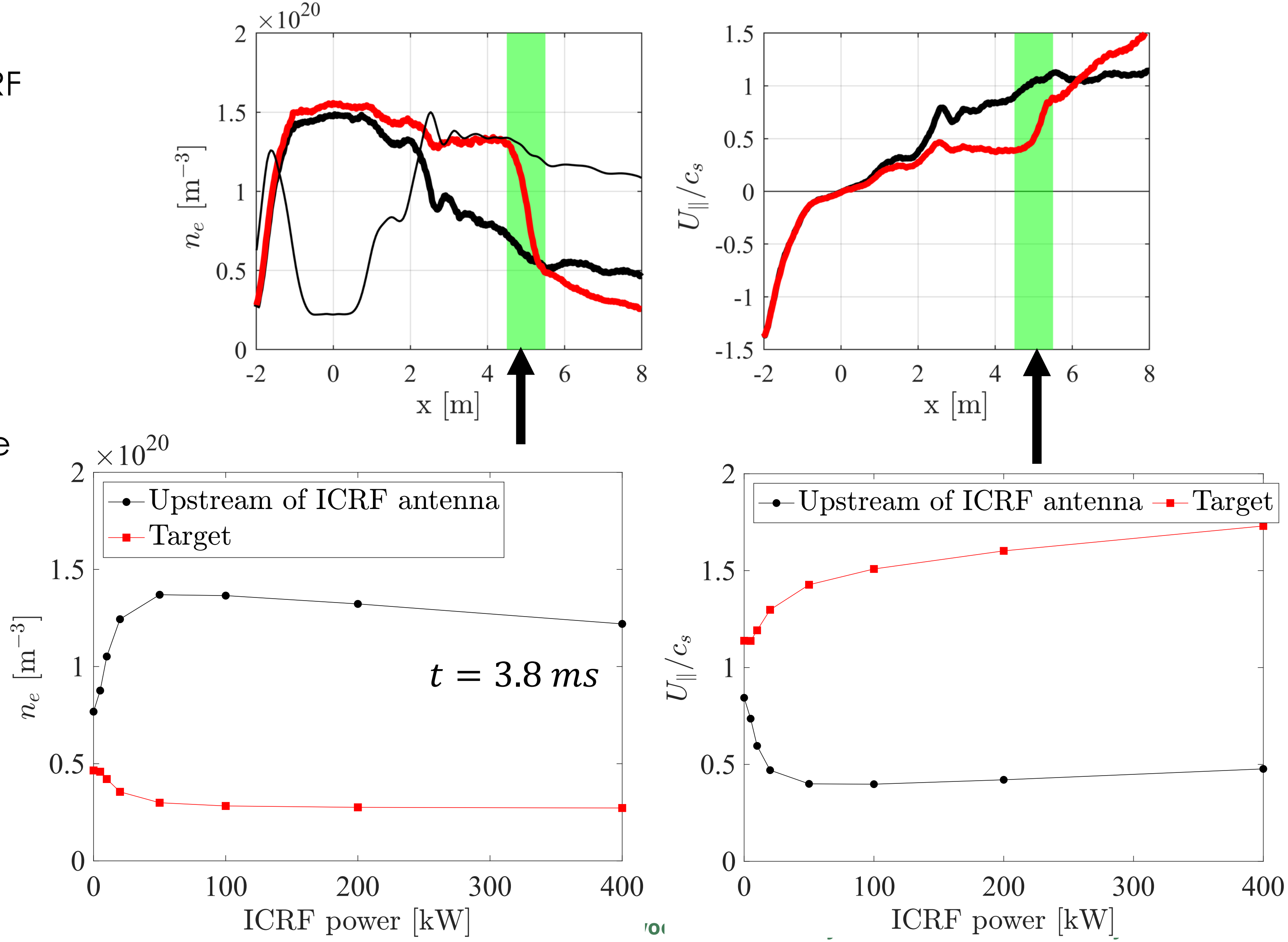
Maxwellian and isotropic

Drifting and Anisotropic distribution

Drifting and two temperature distribution

“Density-drop” at the target saturates beyond 100 kW ICH power

- Scan from 0 to 400 kW absorbed ICRF power
  - Target density drops ~x2
  - Target flow increases ~x2
- “Pile up” of density upstream of ICH antenna
  - Caused by reaction to flow acceleration by RF
- “Density-drop” at the target saturate beyond 100kW



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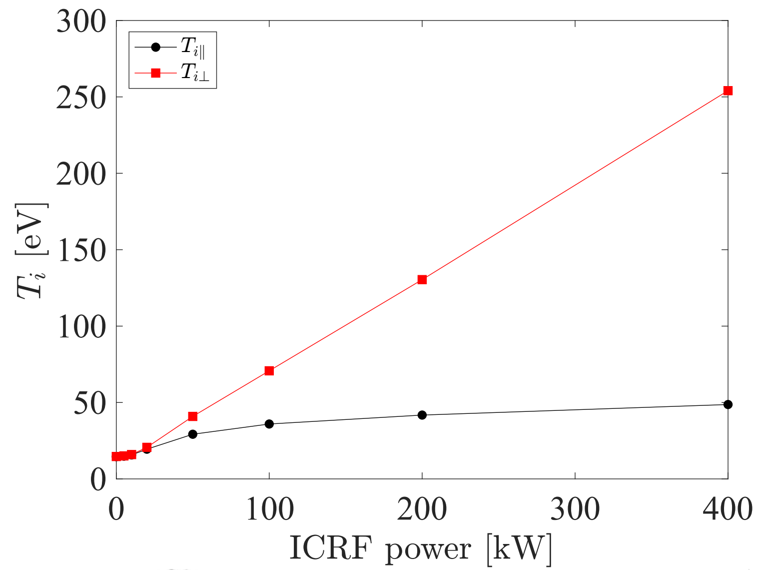
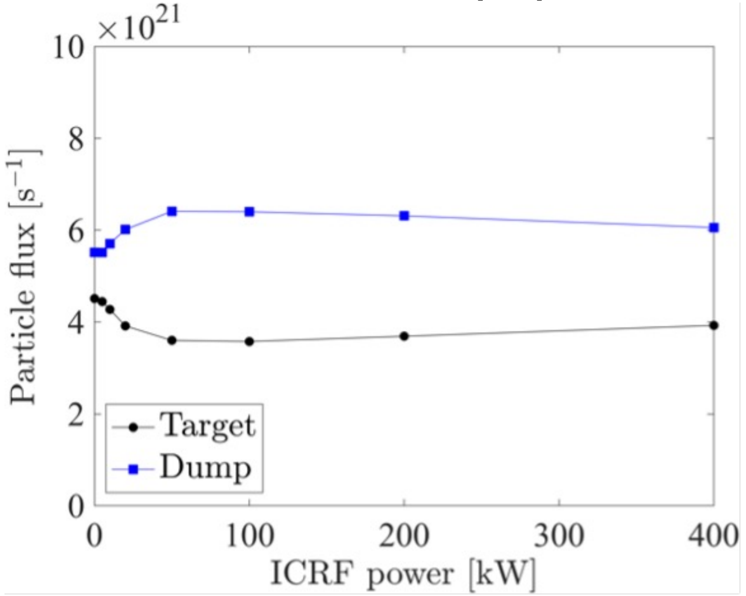
Particle flux at the target weakly affected by ICH; saturates beyond 100 kW

- Temperature anisotropy increases with ICH power
  - $T_{\perp i}$ scales linearly with ICH power
  - $T_{\parallel i}$ saturates with ICH power



- Particle flux at the target
  - Weakly affected by the ICH power (~20%)
  - Saturates beyond 100 KW ICH power
- **Possible solution to the density drop**
  - Local gas recycling at the target with ECH?



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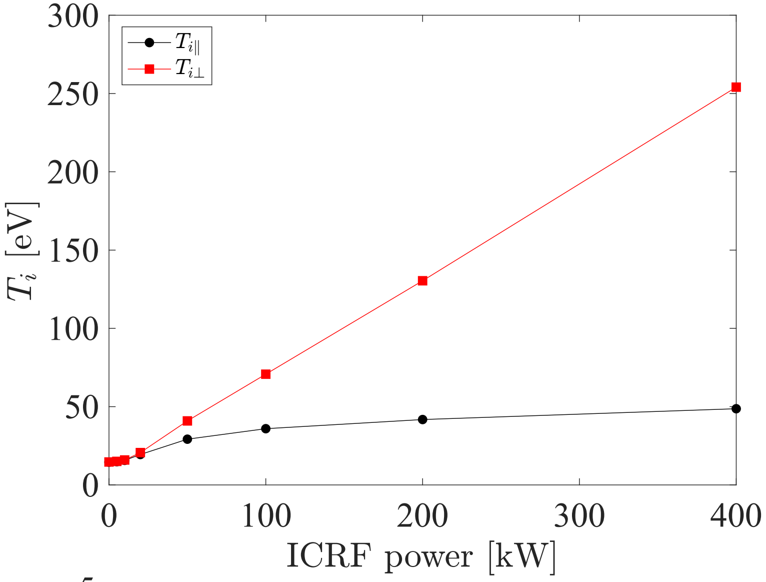
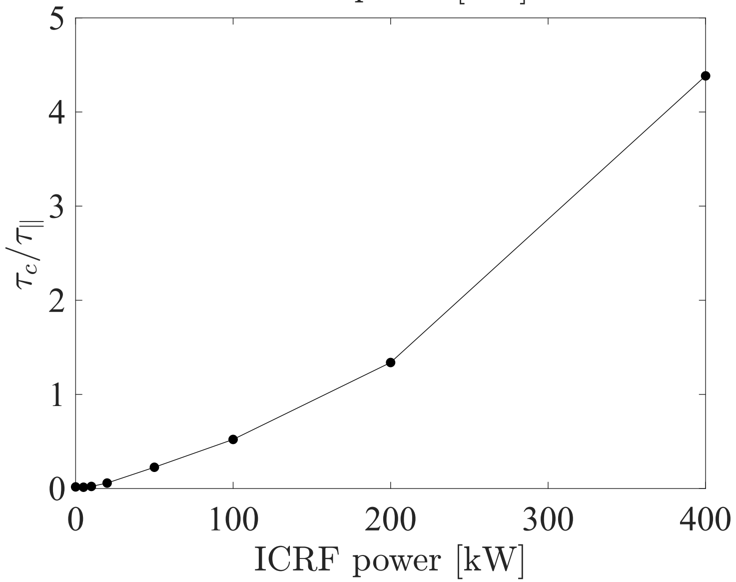
Parallel transport dominates strongly over collisional transport beyond 100kW leading to saturation of plasma profiles at the target.

Analysis on transport time scales:

- At lower ICH power, collisional transport dominates over ions parallel transport ($\tau_c \ll \tau_{\parallel}$)
- Parallel transport is equivalent to collisional transport ($\tau_c \sim \tau_{\parallel}$) at 100kW.
- Beyond 100kW, parallel transport strongly dominates over collisional transport ($\tau_c \gg \tau_{\parallel}$).
- Collisions being less significant beyond 100kW, leads to the **saturation of "density-drop".**





Summary and Future work

- **Summary:**
  - PICOS++: a new massively parallel, quasi-neutral PIC code is developed and can model plasma transport for any open systems in presence of:
    - Coulomb collisions in Fokker -Planck framework
    - Quasi-linear RF heating
    - Volumetric particle source (Isotropic/NBI)

    - **Kumar et. Nucl. Fusion (2023), 63, 036004; Kumar et. al, PPCF (2022), 64, 035005**

  - PICOS++ modeling explains the "density-drop" observed experimentally in Proto-MPEX and suggests possible solutions for this.
  - PICOS++ modeling on MPEX also explains the saturation of the "density –drop" behavior for higher ICH power.
  - The modeling predicts a two-temperature ion distribution at the target in MPEX.
- **Future work**
  - Neutral gas recycling and charge exchange:
    - The neutral gas recycling at the target along with the electron heating to recover the "lost" density at the target.
    - PICOS++ needs to be coupled to neutral code to explore neutral gas recycling and charge exchange
  - ECH modeling with PICOS++
    - Develop PICOS++ with kinetic electrons and fluid ions
    - Computationally challenging with MPI + openMP architecture, needs GPU acceleration
  - Self consistent solution for electron temperature
  - PICOS++ plasma profiles to GITR for impurity transport studies

Thank you!

Questions?