CTTS meeting at the Annual APS DPP Conference, Spokane, WA, October 16, 2022

Scaling Laws for Pellet Ablation in Magnetic Fields based on Lagrangian Particle Simulations

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Talk Outline

- **Other accomplishments:**
  - Brief summary of validation studies using DIII-D experimental data on small neon pellets (PoP, 2022, Sept. issue)
  - 1-page summary of simulation of hydrogen SPI into RE beam in ITER (PoP, 2022, Oct. issue)
  - 1-page summary of paper on massively-parallel Lagrangian particle algorithm (MRC, 2022, submitted)

- **Studies of pellet ablation scaling laws in magnetic fields with resolution of 3D effects (grad-B drift)**

- **Proposed future research directions**

Measurement and simulation of small neon pellet ablation in DIII-D

E. M. Hollmann, N. Naitlho, S. Yuan, R. Samulyak, P. Parks, D. Shiraki, J. Herndal, and C. Marini,
Phys. Plasmas 29, 092508 (2022); doi: 10.1063/5.0106724.

- Studies of the injection of small (< 1 mm) neon pellets into DIII-D, including experimental measurements and numerical simulation results

- In addition to the comparison of pellet lifetimes and ablation rates, a quantity of interest is the “photon efficiency” S/XB (neutral neon ionization events for every photon emitted) which has often been challenging to determine experimentally and previously assumed to be constant along the entire pellet trajectory.

- The diagnostic equipment detects Ne-I (first charge state of Neon) emission from ablating neon pellets and experimental measurements are performed for the strongest visible Ne-I line (640 nm).

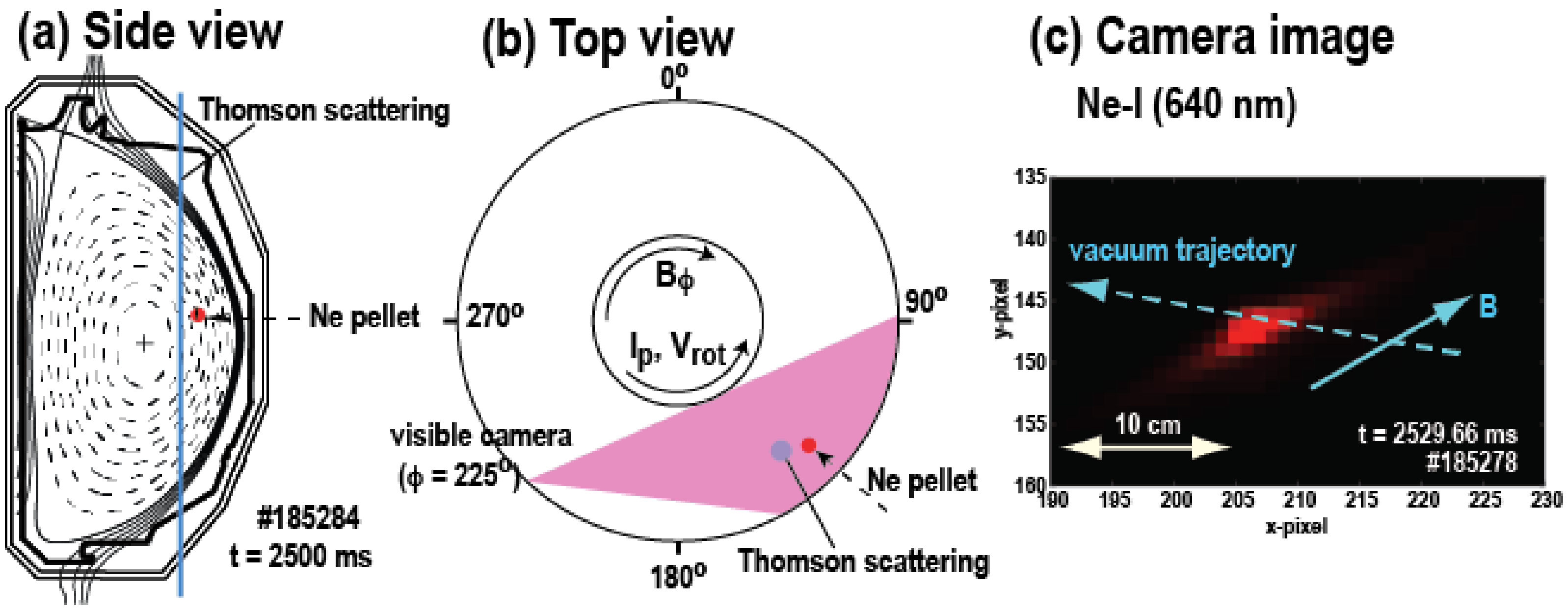
- S/XB is estimated by dividing the estimated initial pellet fragment mass by the measured number of emitted Ne-I photons.

Neon pellet in DIII-D – Experimental Setup

- Small neon pellets (mass = 1.7 Torr-L $\Longrightarrow r_p = 0.65$ mm), one per plasma discharge, were fired inward radially at typical velocities ≈ 200 m/s from the outer midplane

- Diagnostics used were a tangentially-viewing fast camera, Fig. (b), to image the neon pellet ablation plume, Fig. (c), and a vertical Thomson scattering (TS) system to measure background plasma $T_{e\infty}$ and $n_{e\infty}$ profiles.

- The diagnostic equipment was able to obtain good Ne-I camera data for **7 different pellets**. The small neon pellets were observed to break into a main large pellet followed by several smaller fragments. Using a uniform mass normalization, we estimate a mass of 1.1 Torr-L ($\boldsymbol{r_p = 0.56}$ **mm**) for the main (larger) pellet.

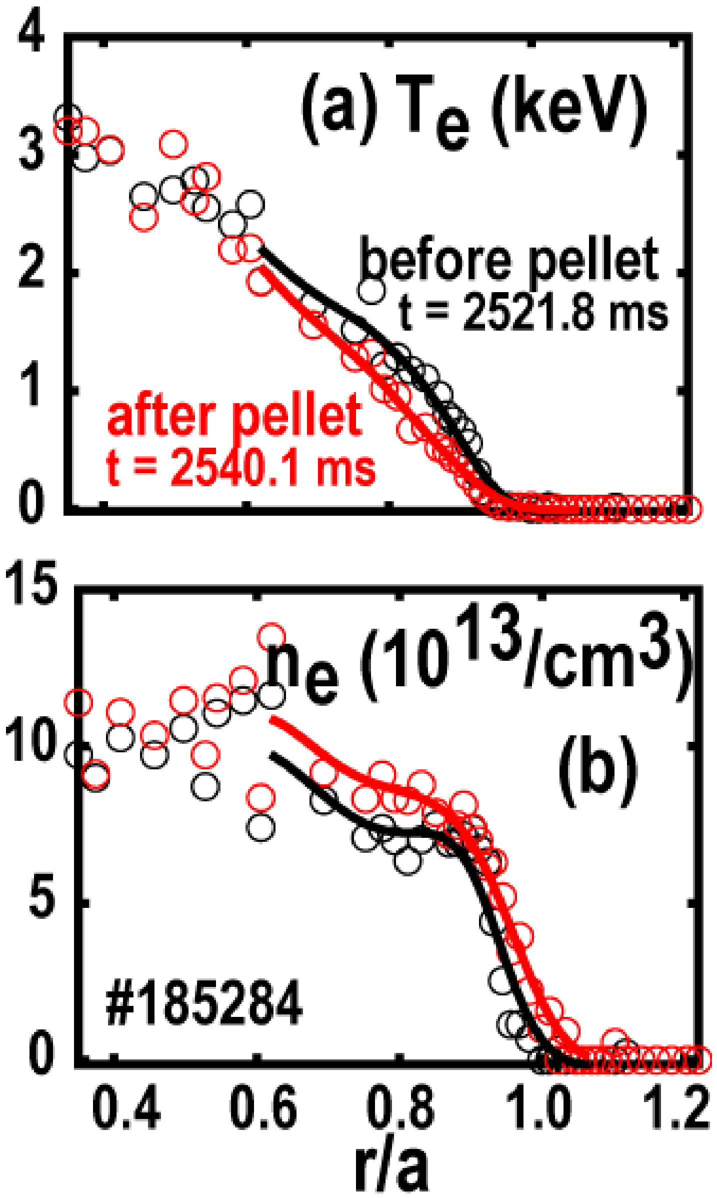


- In Fig. (c), the pellet emission tends to be elongated along the magnetic field direction **B**, exhibiting a similar cloud shape as in our simulations. The camera is not able to capture the transverse drift dynamics

Neon pellet in DIII-D – Simulation Setup

- We focus on a specific pellet shot which resulted in the highest total integrated Ne-I brightness. The corresponding plasma parameters before (black) and after (red) this pellet is injected are shown on the right
- To model the neon pellet ablation rate and S/XB, two numerical models are used sequentially: the LP pellet code and the PrismSPECT collisional-radiative code (**Bailey et al. Physics of Plasmas, 2009):**

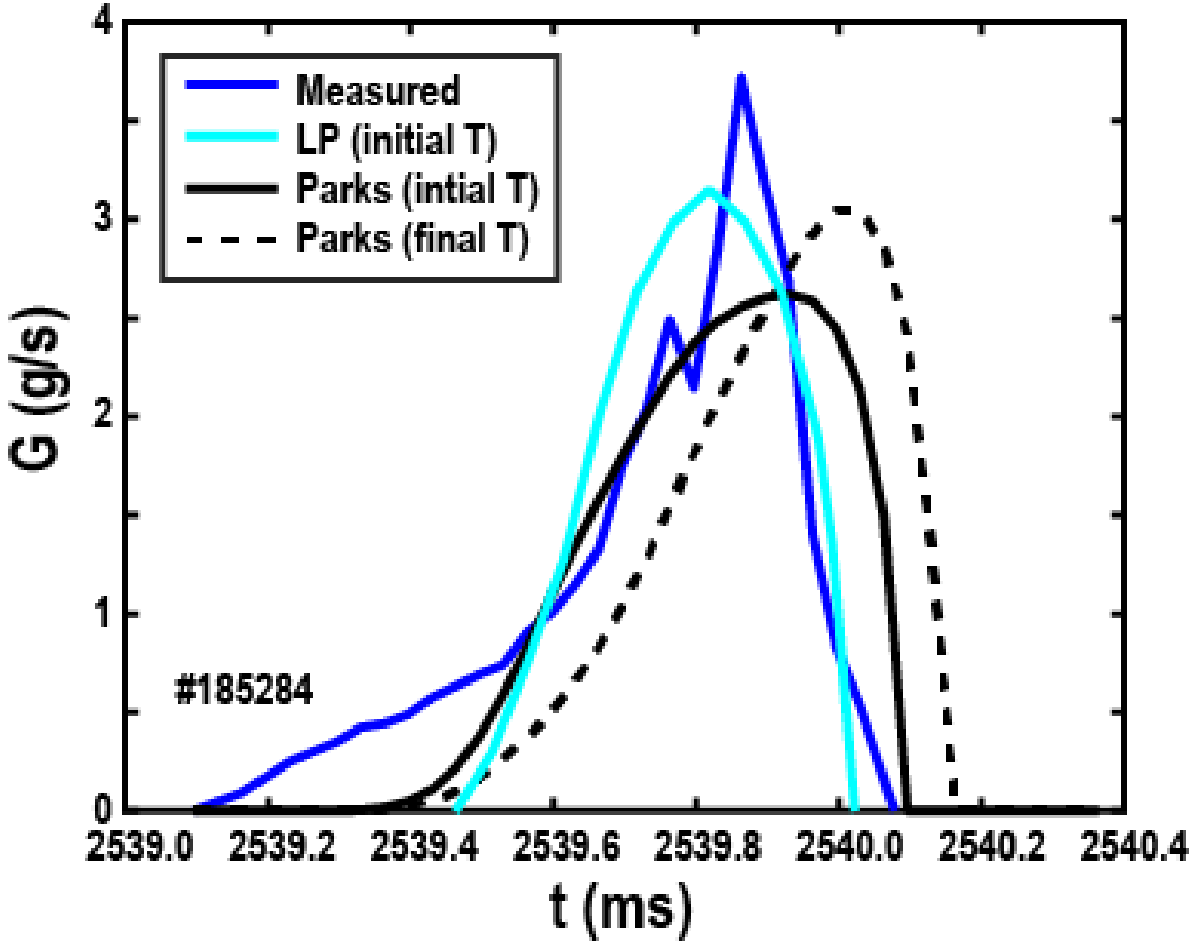
1. Dynamic LP simulations resolve the ablation process, compute the ablation rate, and the reduction of the pellet size along the pellet trajectory. At each radial pellet position, LP provides distribution of states in the 3D ablation cloud. In addition, we computed evolution of temperature and density on a selected subset of Lagrangian particles.
2. These time-dependent functions are then used by PrismSPECT to calculate the time-dependent charge state and spectral emissivity of a fluid element moving away from the pellet and estimates S/XB (E.Hollmann)



Neon pellet in DIII-D: Measured and simulated ablation rate

- The ablation rate G vs time can be experimentally measured by assuming that S/XB is a constant. As will be discussed later, numerical results indicate that S/XB is not actually constant along the pellet trajectory; however, this approximation can still be used to give a rough first approximation of the pellet ablation curve, and the end point (pellet burn-through time and distance) is still completely accurate.

- The LP ablation rate (cyan), based on the initial (pre-pellet) temperature profile is in reasonably good agreement with the experimental data (blue). Also, the prediction of the most recent NGS analytic model is shown by the black solid and dashed curve corresponding to initial (pre-pellet) and final (post-pellet) plasma profiles.

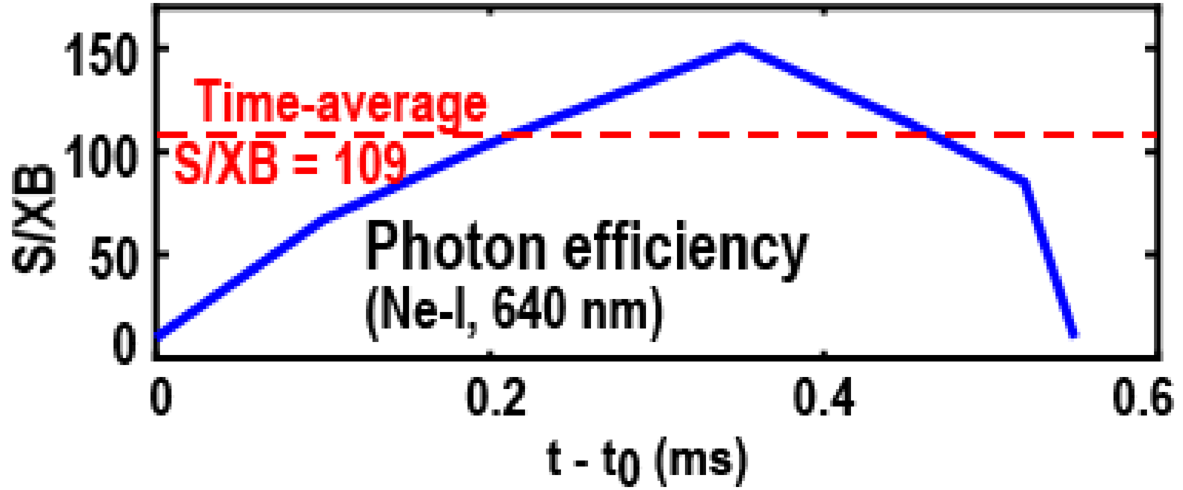


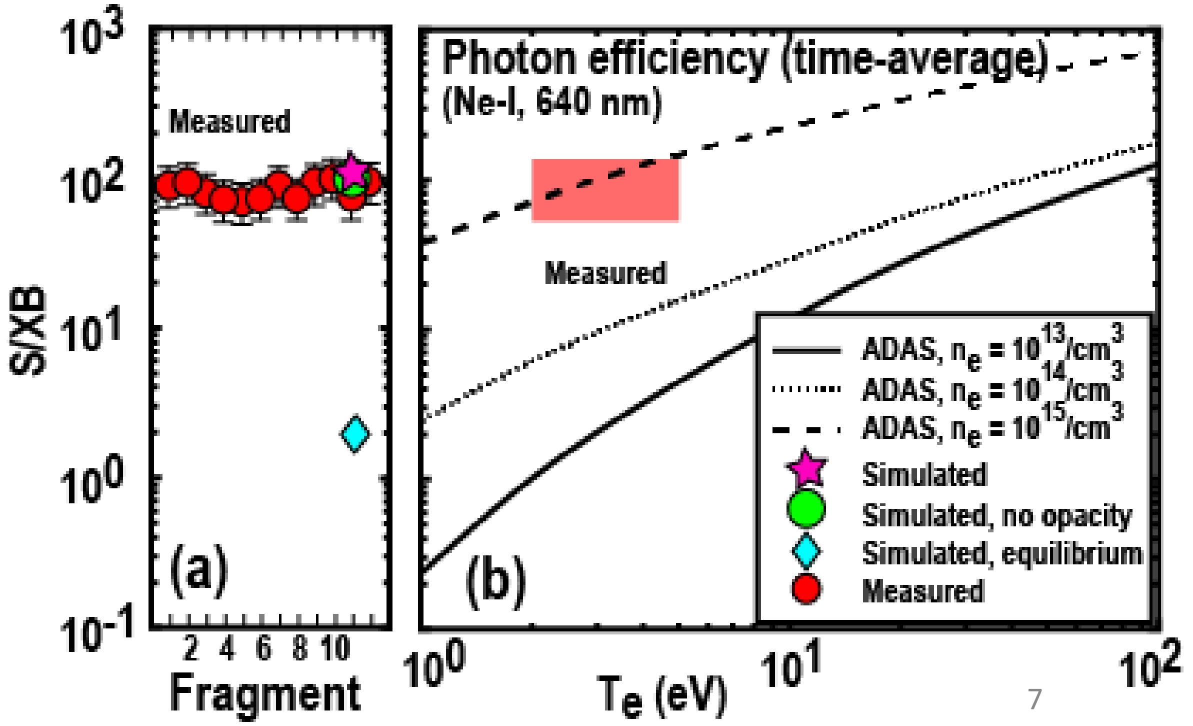
Neon pellet in DIII-D: measured and simulated S/XB

- S/XB estimated by PrismSPECT using LP data is seen to be not constant along the pellet trajectory but rises as ablation rate rises. The time-average value is **S/XB ≈ 109**.

- Trajectory (time) average values of S/XB (measured and modeled) for Ne-I 640 nm are shown in bottom figure. The red circles are measured values, each corresponding to one pellet injection shot. Other markers are values predicted by LP + PrismSPECT: pink star is the time-average of top figure, green circle is the same simulation but with opacity turned off and cyan diamond is the same simulation but with steady-state(equilibrium) kinetics used in PrismSPECT

- The average measured Ne-I 640 nm photon efficiency **S/XB ≈ 100**. Time-dependent kinetics are crucial here: S/XB is predicted to drop by almost two orders of magnitude when equilibrium (rather than time-dependent) kinetics are used in PrismSPECT

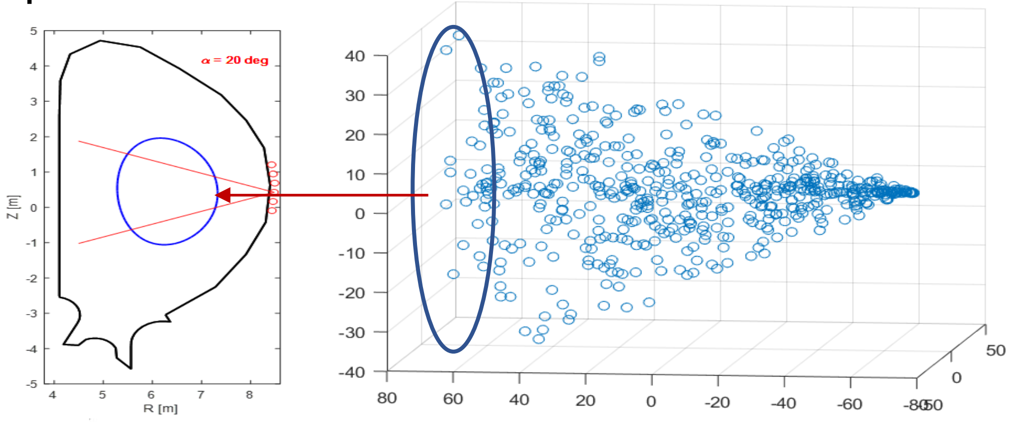




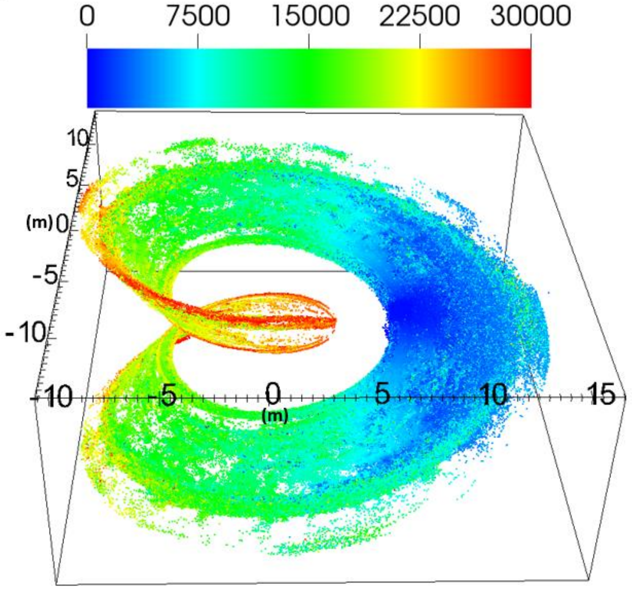
Lagrangian Particle Simulation of SPI into Runaway Beam in ITER

S. Yuan, N. Naitlho, R. Samulyak, E. Nardon, B. Pegoruie, P. Parks, M. Lehnen, Phys. Plasmas 29, (2022), October issue.

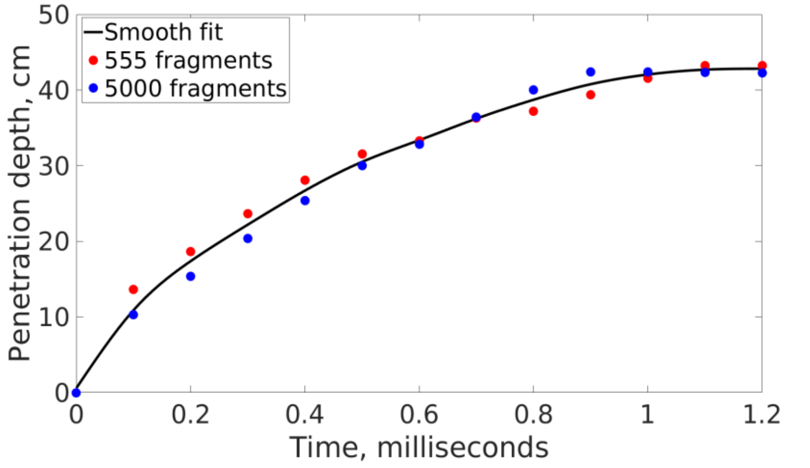
- Lagrangian particle pellet / SPI code has been extended to include physics models for the injection of hydrogen pellets and SPI into RE beam in ITER



- Simulations using 550 and 5000 SPI fragments quantified several physics effects on the ablation cloud dynamics
- Penetration depth of SPI cloud into the runaway beam was computed
- Global dynamics of the ablation was obtained
- Top left: schematic of the SPI injection into the RE beam
- Bottom left: long-scale dynamics of SPI cloud. At 1.7 ms, the cloud reconnects at q=2.



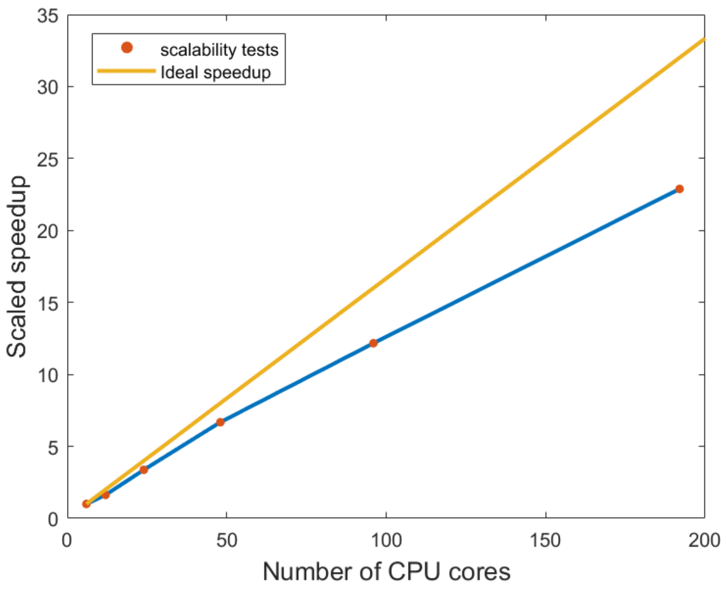
- Bottom right: penetration depth of SPI cloud into RE beam with density ramp

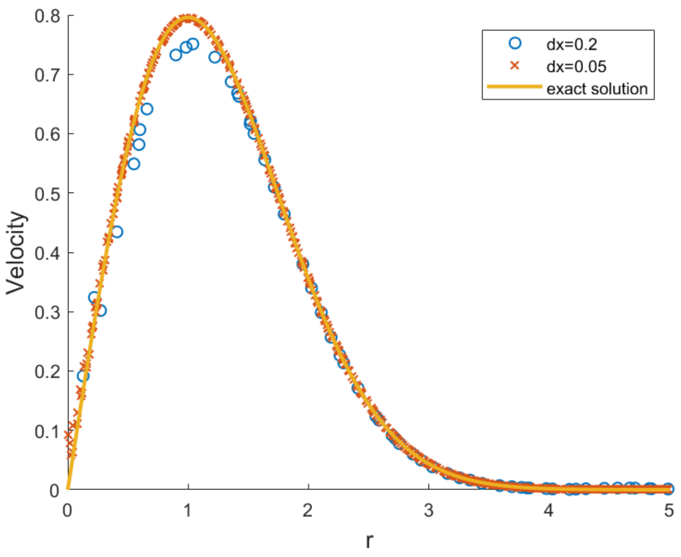


Massively Parralel Lagrangian Particle Code

S. Yuan, N. Naitlho, R. Samulyak, MRC, 2022, submitted

- Description of parallel algorithms for particle-based computing in non-uniform domains based on parallel forests of K-trees: optimal particle distribution, migration / parallel communication of particles between subdomains during their motion, search for particle neighbors, discretization of operators on particle-based stencils, solver schemes.
- Verification using analytic solutions for the Yee vortex in 2D and 3D
- Strong and weak scalability tests
- Brief summary of current applications





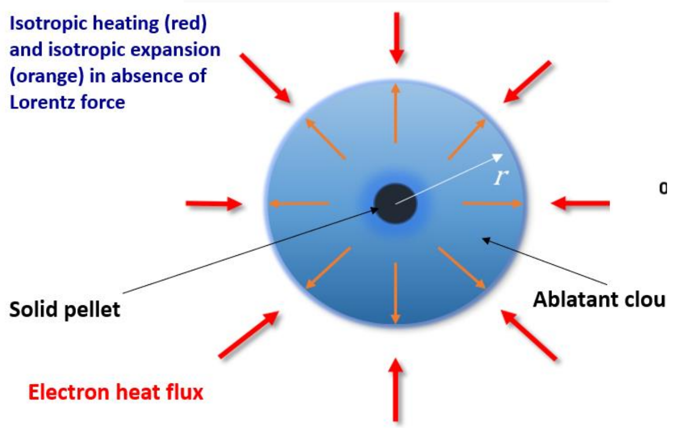
Left: Weak scalability of the LP code. The speedup using 200 CPU cores was about 72% of the ideal speedup. No speedup saturation was observed.

Right: Radial scatter plots of velocity of particles in Yee vortex simulations demonstrating convergence to the exact solution. Second or higher convergence order was observed.

Scaling Law for Spherically Symmetric Pellet Ablation

- **Theoretical model**
  - ➔ Parks' Neutral Gas Shielding (NGS) model (Nuclear Fusion, 1977):
    - Hydrodynamic model developed for hydrogen pellets, assumes spherical symmetry both for the electron heating and the expansion of the ablation cloud
    - Scaling law for pellet ablation rate

$$G \sim T_{e\infty}^{\frac{5}{3}} n_{e\infty}^{\frac{1}{3}} r_p^{\frac{4}{3}}$$



- LP simulations have been carries out for neon and deuterium pellets ranging from 2 mm 5 mm in radius, and background plasma with temperatures from 1 to 5 keV and densities from 0.5 to 3 x 10^{14} 1/cc

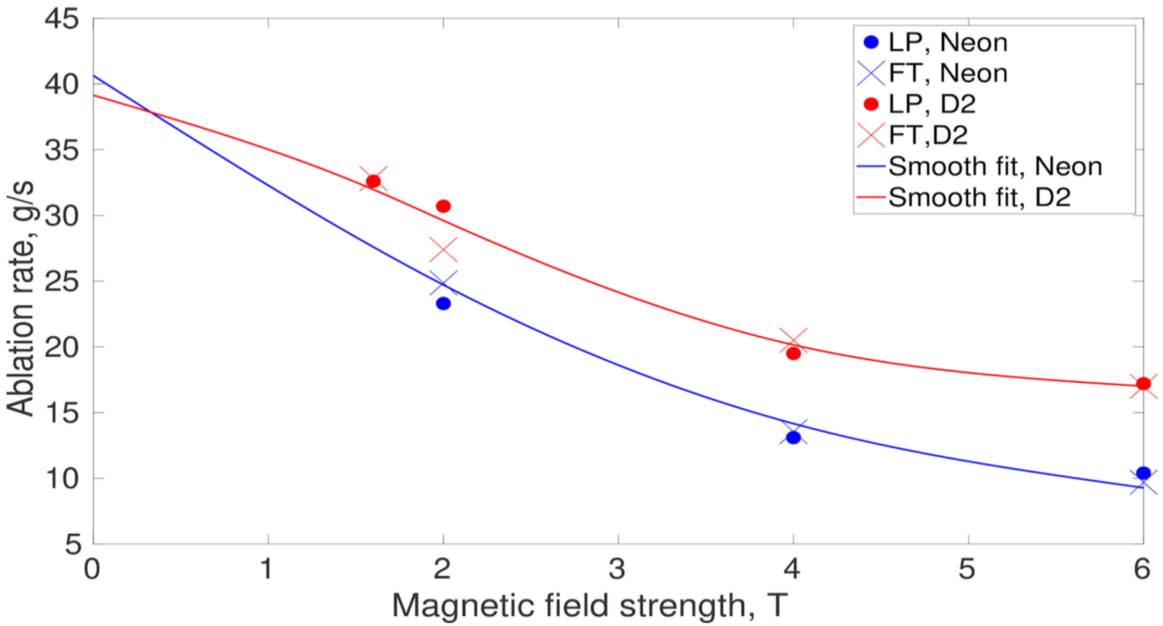
- The agreement with the theory was typically within 1% and was always smaller than 2%

- LP code was also in very good agreement with 1D spherically symmetric FronTier simulations

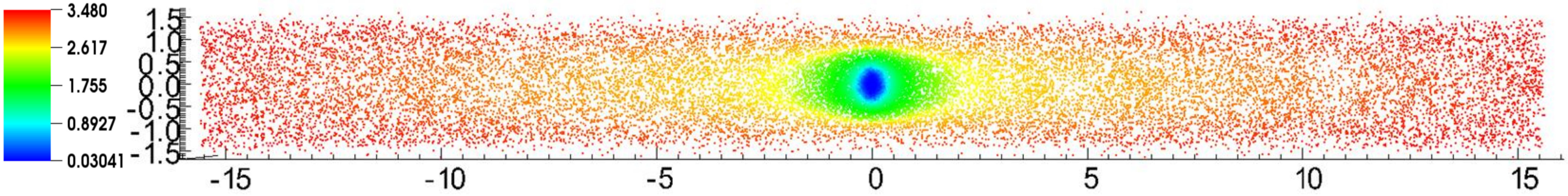
The pellet ablation also depends on the magnetic field and tokamak major radius: problem in a 5D space!

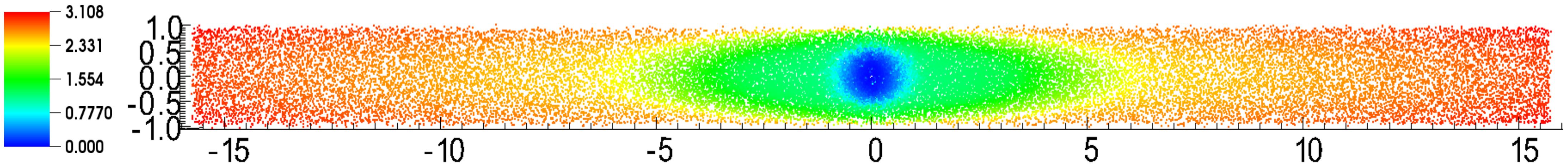
$G = (T_e, n_e, r_p, B, R)$

Code verification by comparing LP and FronTier codes: Axisymmetric MHD Simulations

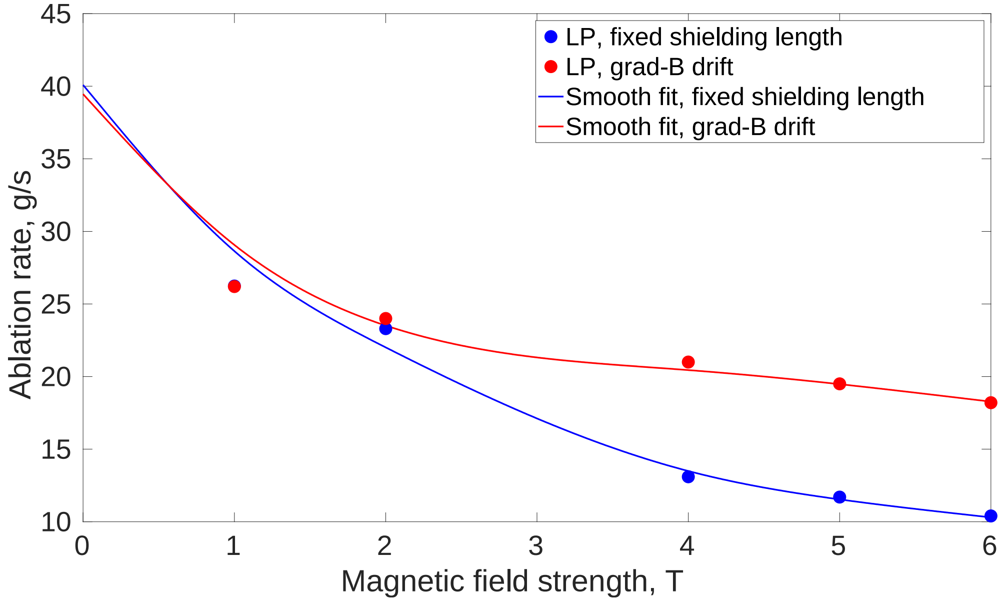


- Ionized ablation flow moves predominantly along magnetic field lines; density and pellet shielding increases
- Higher magnetic fields lead to narrower pellet clouds, higher densities and lower ablation rates. Significant reduction of the ablation rate was observed
- Both codes are in good agreement on the reduction of the ablation rate
- **Image**: 2D Temperature distribution (slice through the pellet center) from LP simulations of a Neon pellet. Top: B = 2T, Bottom: B = 6T



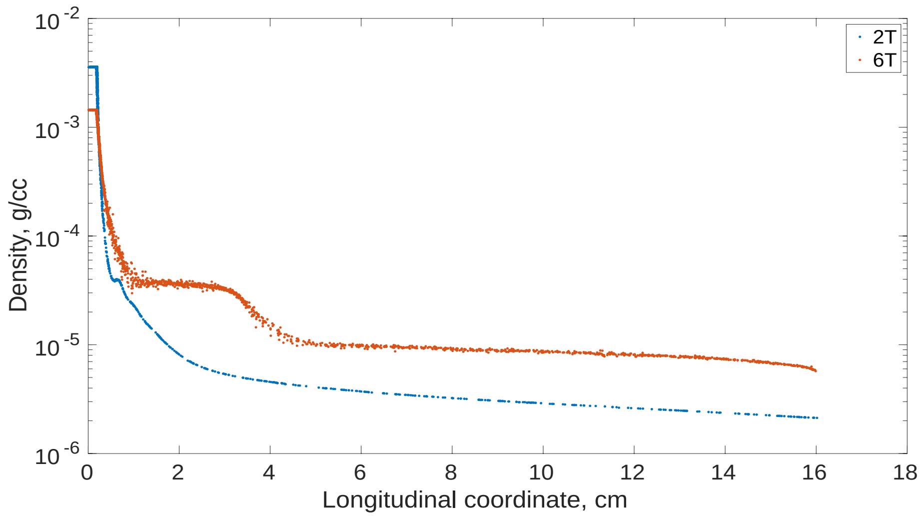


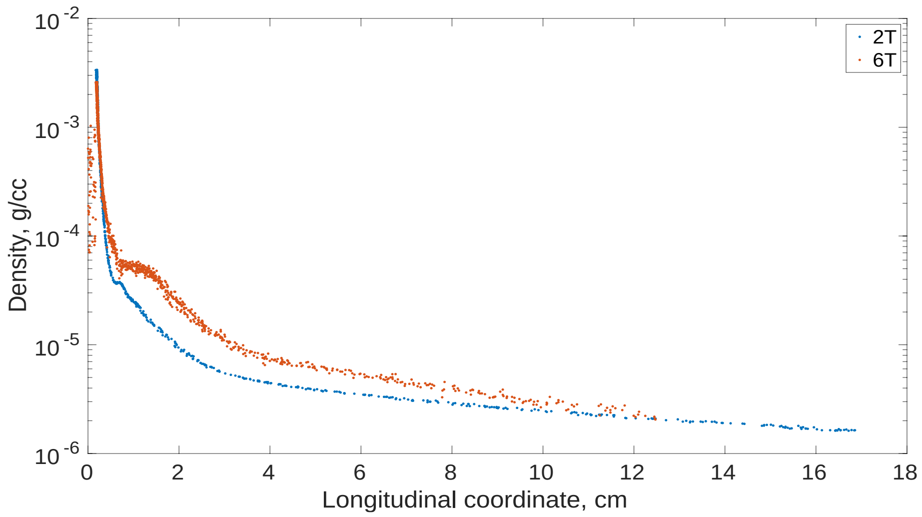
Ablation rates in magnetic field for Neon and Deuterium pellets with grad-B drift



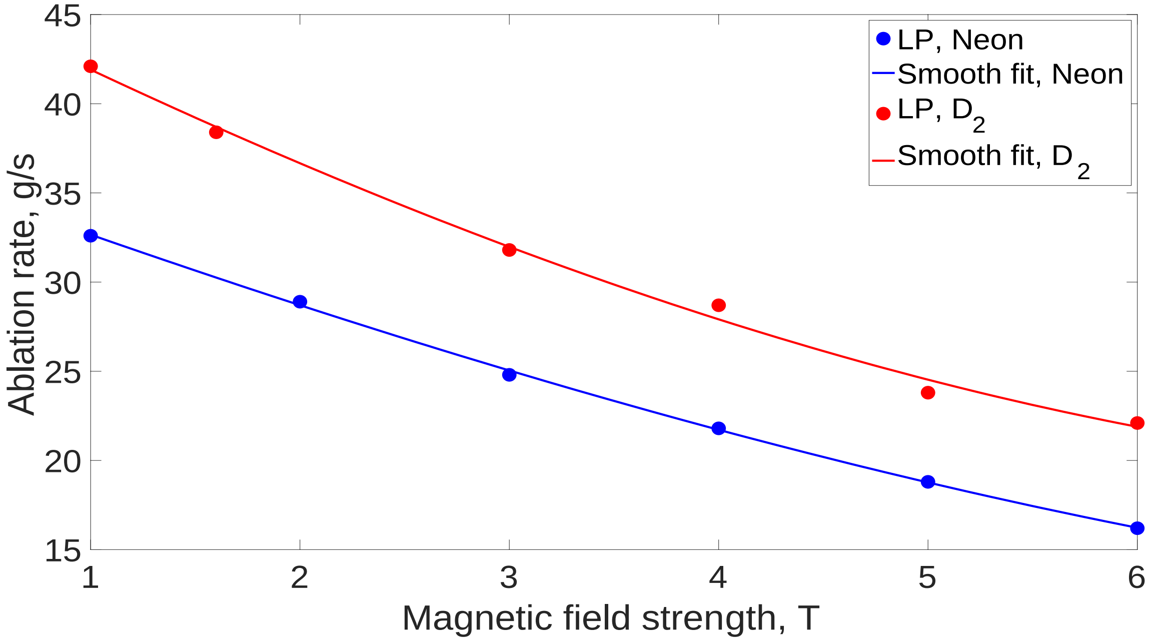
- With grad-B drift, we observe **weaker reduction of the ablation rate** in magnetic field compared to simulations with fixed shielding length
- The shielding length decreases with the increase of the magnetic field
- Without the grad-B drift, the ablated material is completely confined to a narrow ablation channel by the Lorentz force. With the increase of the magnetic field, the ablation channel narrows, increasing the density in the channel, the pellet shielding, and reducing the ablation rate. Such a confinement does not take place in the presence of grad-B drift : the ablated material drifts across magnetic field lines and makes the shielding effect less sensitive to the magnetic field changes.
- Comparison of cloud density for 2T and 6T magnetic fields for simulations with fixed shielding length (left) and grad-B drift (right)

B (T) Neon	Shielding length, cm	G(LP, g/s)
1	21	26.2
2	17	24
4	15	21
5	13.5	19.5
6	12.5	18.2





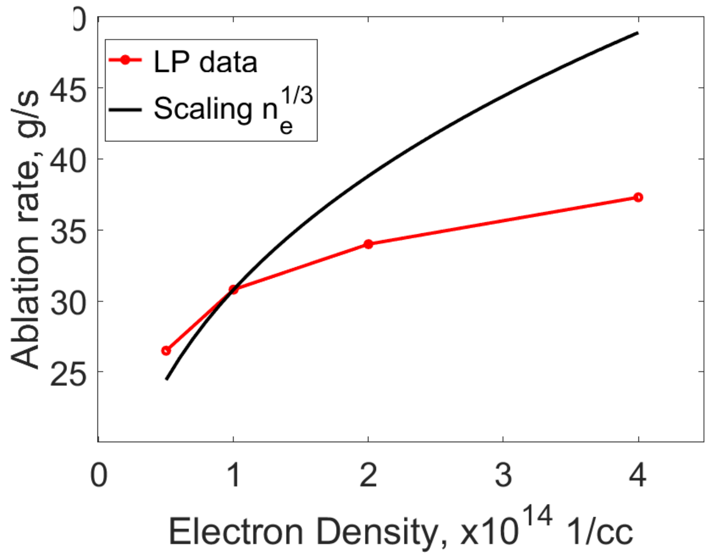
Pellet Ablation rates with grad-B drift and constraint R[m] = B[Tesla]



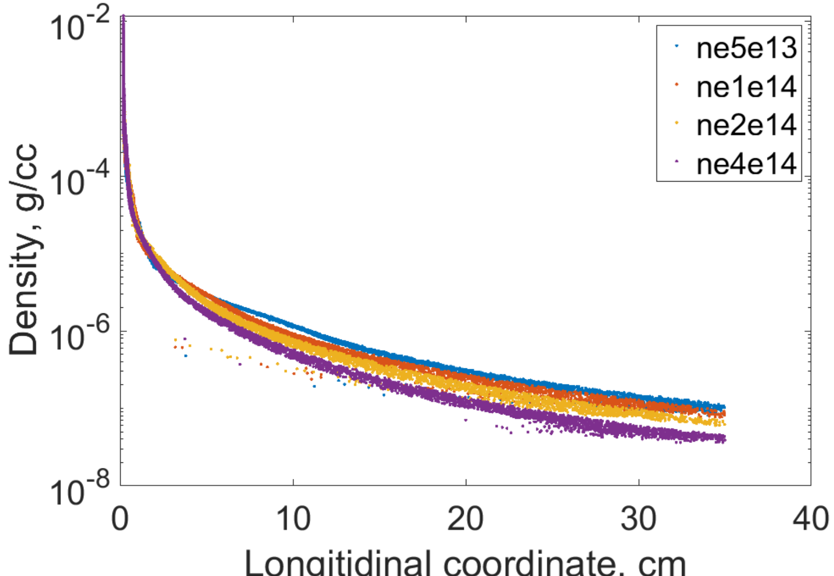
- The most important tokamak parameter influencing the grad-B drift is the major radius R
- Since the ratio of the peak magnetic field in Tesla to the tokamak major radius in meters is close to unity for all practical tokamaks, including ITER, new simulations use this constraint (R[m] = B[Tesla])
- Results for 2 mm neon and deuterium pellets are shown
- For 2 mm deuterium pellet in 1.6 T field, numerical result, 38.4 g/s, is in excellent agreement with experimental value 39 g/s.

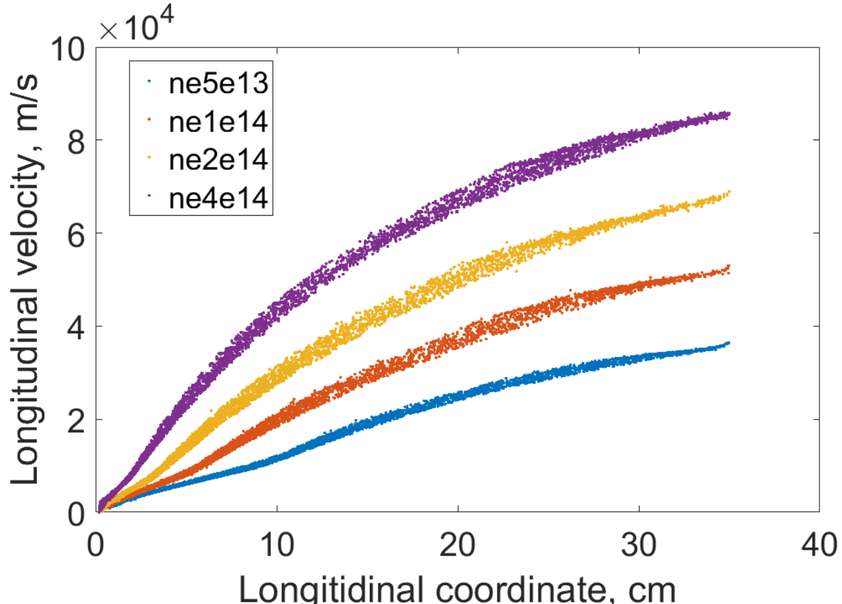
Ablation rate dependence on electron density

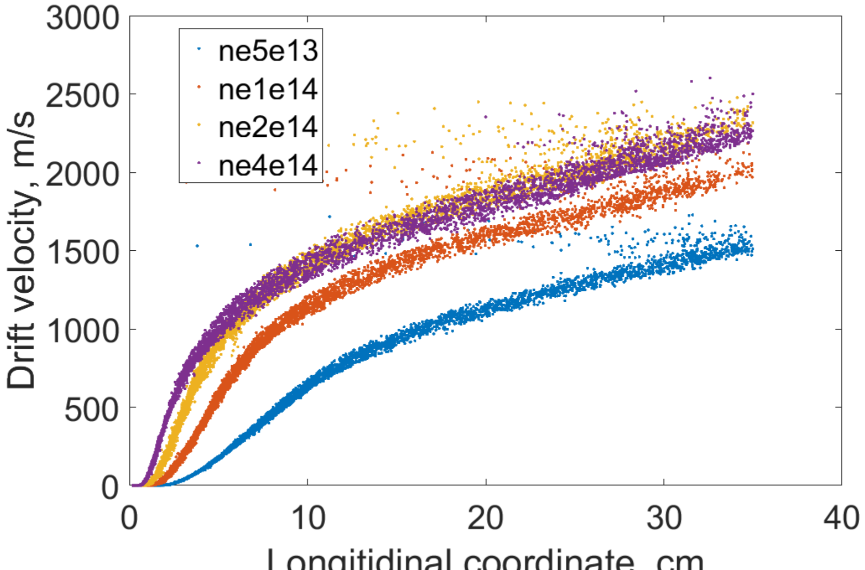
- The ablation rate is lower for high electron density values compared to the scaling law for spherically-symmetric ablation
- Larger amount of energy is deposited in the cloud at higher n_e. Longitudinal velocity significantly increases while the drift velocity increase rate is smaller
- This leads to the formation of longer and narrower ablation clouds with the increase of n_e while the density slightly decreases
- Smaller amount of energy reaches the pellet surface with the increase of n_e compared to the scaling law of $n_e^{1/3}$



Dependence of ablation rate on background plasma electron density for 2 mm radius pellet in T=2keV plasma with R[m] = B[Tesla] = 4.





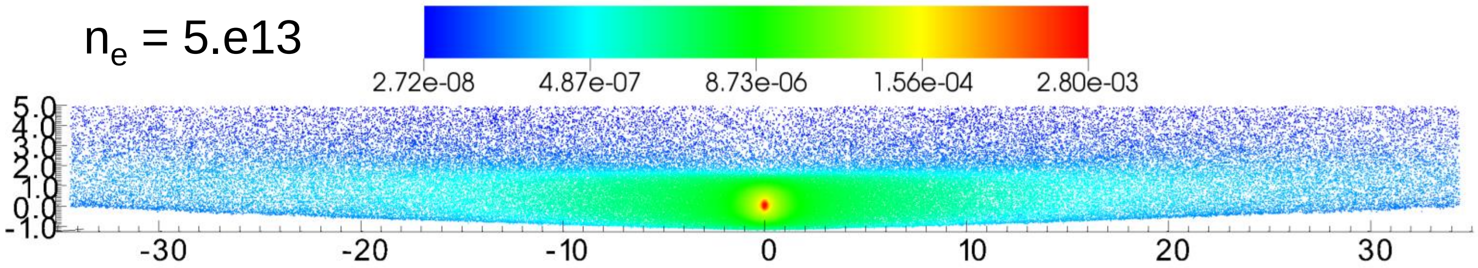


Ablated cloud density

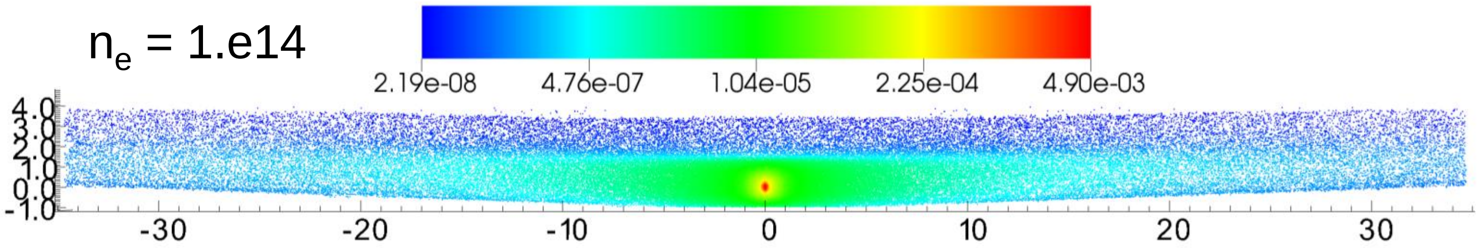
Distribution of density (g/cc, log scale) on thin slices through the pellet center in the direction of grad-B drift

r_p = 2 mm
T_e = 2 keV
R[m] = B[Tesla] = 4

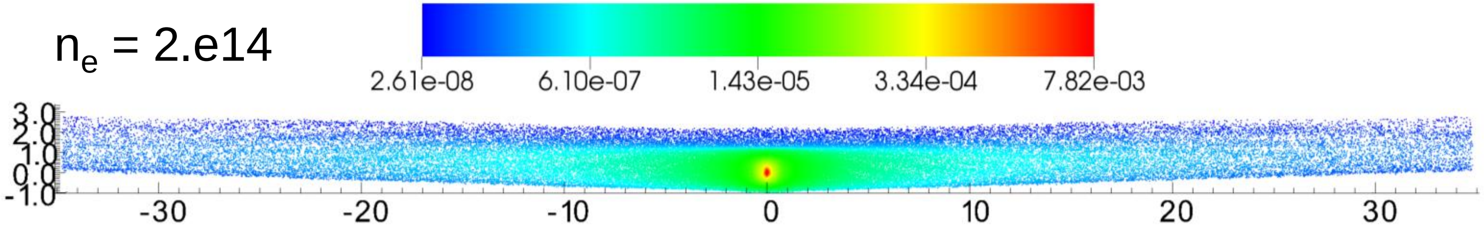
n_e = 5.e13



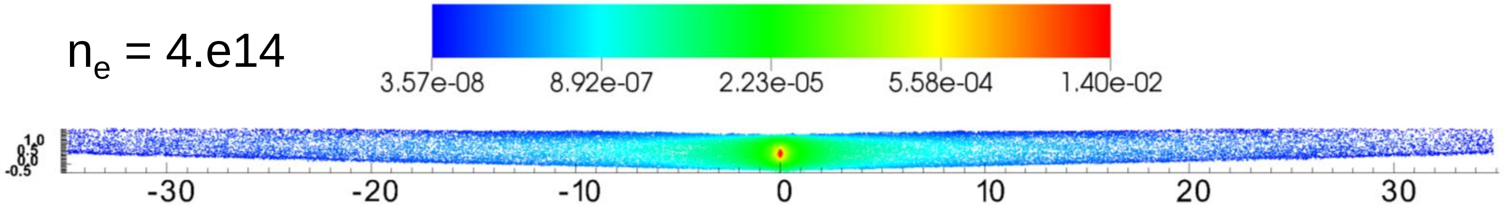
n_e = 1.e14



n_e = 2.e14

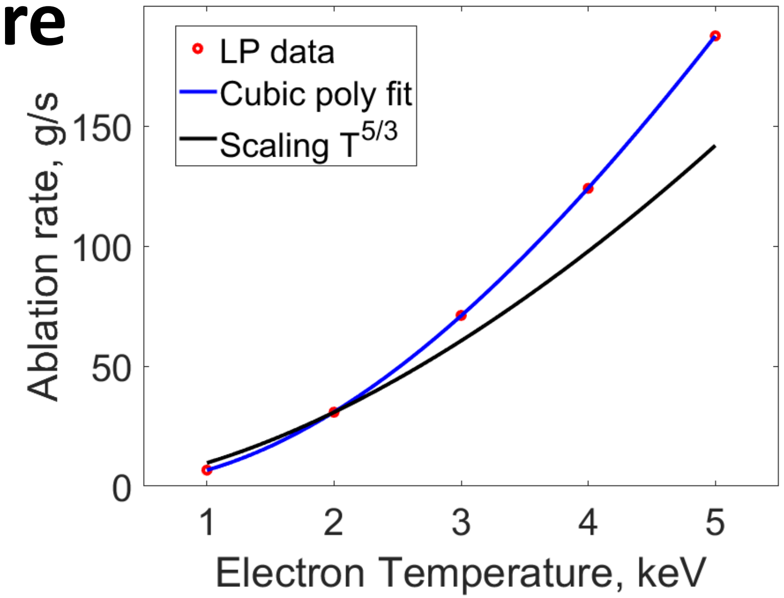


n_e = 4.e14

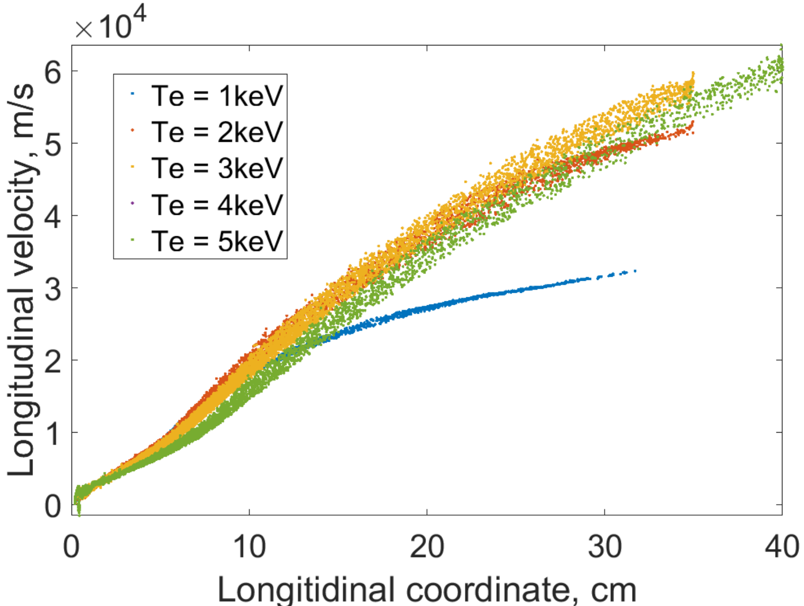


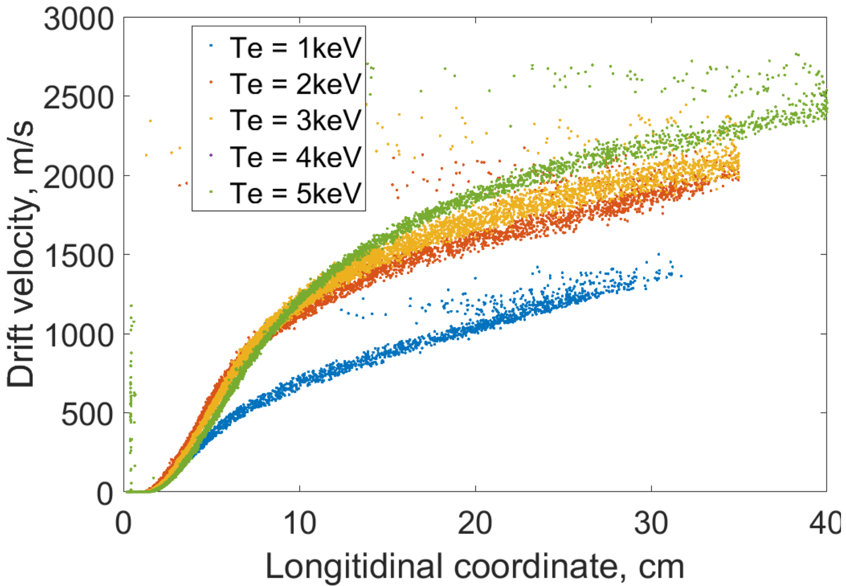
Ablation rate dependence on electron temperature

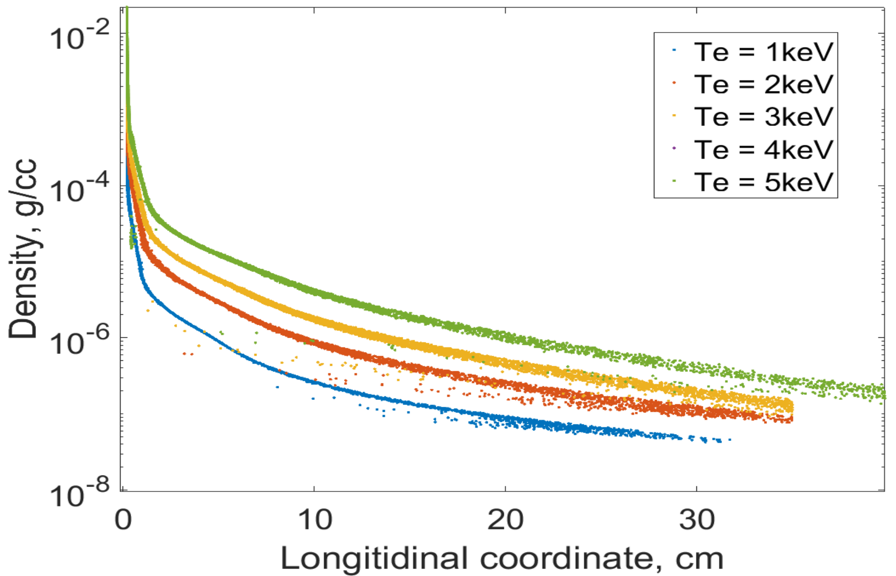
- The ablation rate is higher for high electron temperature values compared to the scaling law for spherically-symmetric ablation
- The increase of the longitudinal velocity is much smaller compared to the n_e dependence while the drift velocity increase is similar.
- This leads to the formation of wider ablation clouds with the increase of T_e while the density increases because of very rapid increase of the ablation rate.
- Larger amount of energy reaches the pellet surface with the increase of T_e compared to the scaling law of $T_e^{5/3}$



Dependence of ablation rate on background plasma Te for 2 mm radius pellet in plasma with ne=1.e14 1/cc and R[m] = B[Tesla] = 4.



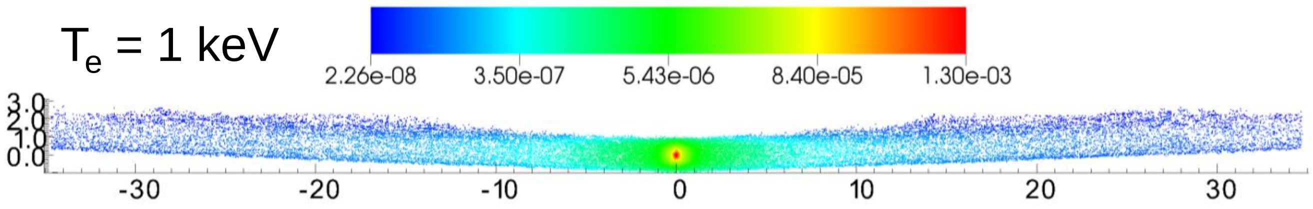


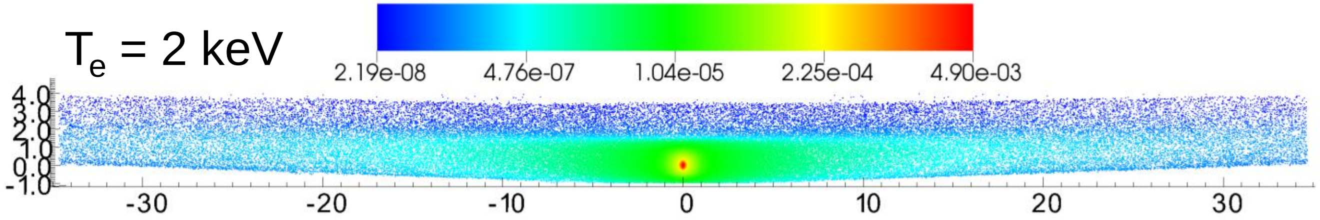


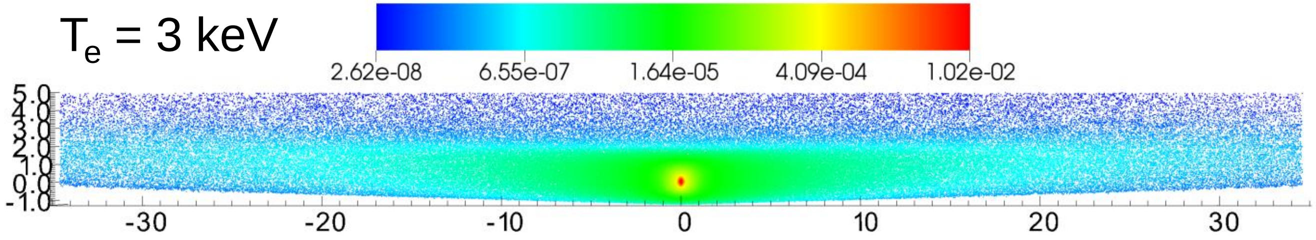
Ablated cloud density

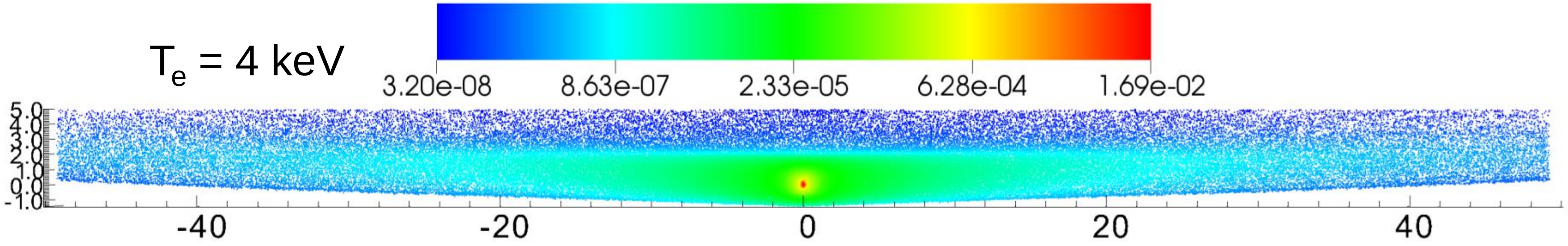
Distribution of density (g/cc, log scale) on thin slices through the pellet center in the direction of grad-B drift

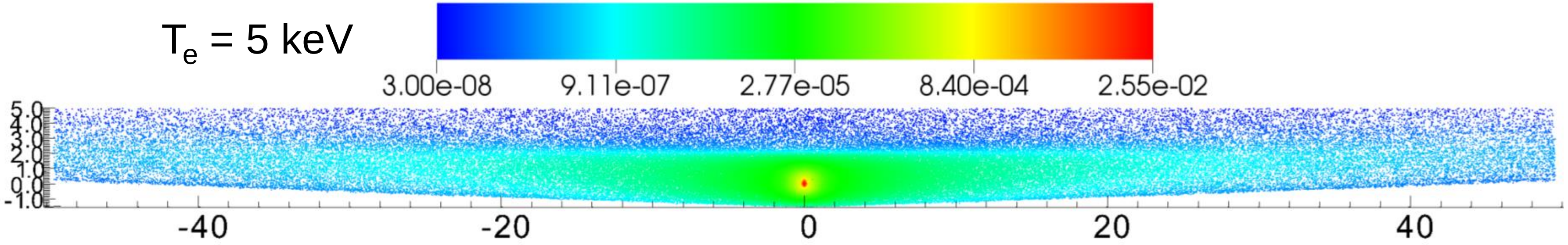
r_p = 2 mm
n_e = 1.e14 1/cc
R[m] = B[Tesla] = 4









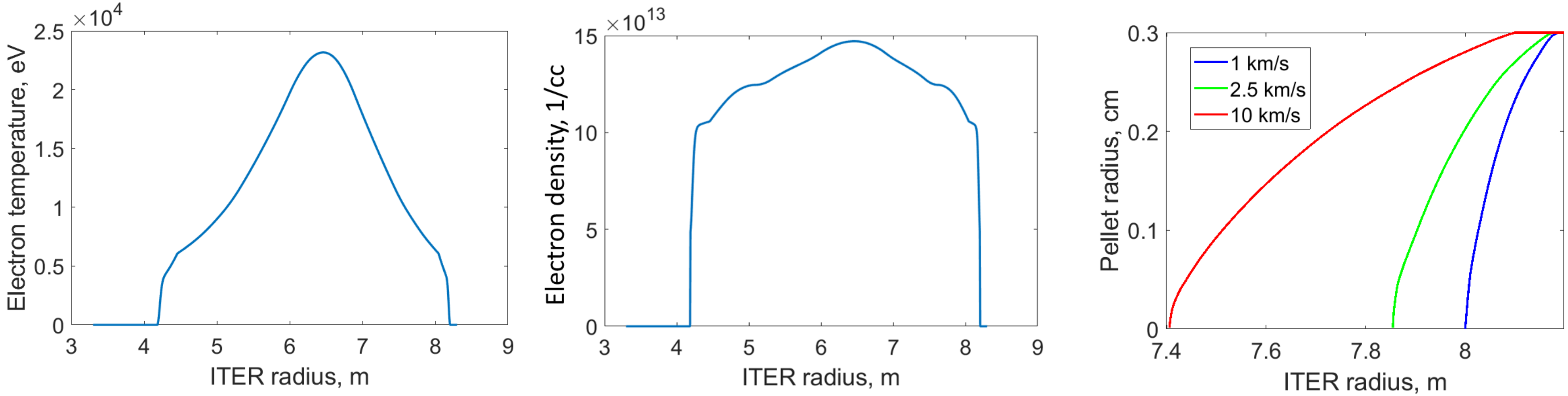


Summary of studies of ablation rate scaling with pellet raduis

- Good agreement with theoretical scaling laws for small pellets in weak magnetic fields (1-2 T)

- Reduction of ablation rate compared to the theoretical scaling law for large pellets
  - 25% reduction of the ablation rate for 5mm radius pellet at B[T] = R[m] = 1.6

- **Simulations with dynamically reducing pellet radii** have been performed using typical DIII-D and ITER plasma profiles
  - The ablation rate remains quasi-steady-state along the pellet trajectory: an instantaneous ablation rate is within few % from the corresponding steady-state ablation rate at given instantaneous background plasma state
  - Typical time scale for (approximately) reaching a steady state after variations of plasma state is 10 – 20 microseconds (longer time corresponds to high magnetic fields, large pellets etc.)
  - During this time, a 200 m/s pellet moves only by 0.2 – 0.4 cm



Simulations of fast 3mm radius pellets injected into ITER from LFS.

Studies of Scaling Laws: Conclusions

- 3D Lagrangian particle simulations with spherically symmetric initial conditions and sources are in good agreement with theoretical scaling laws

- 3D LP simulations with cylindrically symmetric initial conditions and sources are in agreement with FronTier pellet code. Simulations predict strong reduction of the ablation rate in magnetic fields of increasing strength

- 3D LP simulations with grad-B drift predict weaker effect of magnetic fields on the ablation rate. The ablation cloud is not confined by narrow ablation clouds as the ablated material drifts across magnetic field lines, affecting the pellet shielding

- In strong magnetic fields and at large values of the background plasma density and temperature and pellet radii, pellet ablation rates significantly deviate from the theoretical scaling law
    - The ablation rate is lower compared to the theoretical scaling law at large values of the background plasma density and pellet radius
    - The ablation rate is higher compared to the theoretical scaling law at large values of the background plasma temperature

- Typical time scale for (approximately) reaching a steady state after variations of plasma state is 10 – 20 microseconds
- For simulations with non-constant plasma parameters and dynamic reduction of pellet radius, the instantaneous ablation rate is close it its steady-state values at any point of the pellet trajectory

Proposed Future Research Directions

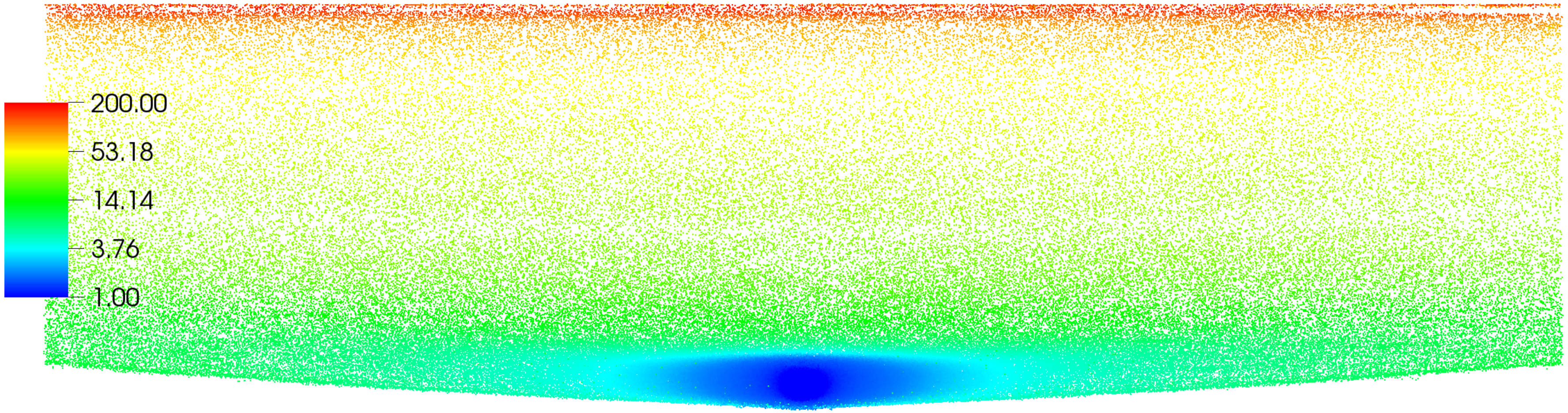
Task I. Explain the phenomenon of striation instabilities of ablation clouds

(suggestion of ITER colleagues Bernard Pegourie and Eric Nardon)

- Striation instabilities, which manifest themselves in periodic separation of ablation clouds from pellets, and not fully understood
- Several causes of striations have been proposed:
  - Pellet crossing rational surfaces, presence of magnetic islands (Pegourie)
  - Pellet going through its own cloud after it becomes sufficiently conductive (unlikely)
  - Distortion of magnetic field lines by pellet clouds.
  - P. Parks suggested that striations could be caused by rotational instabilities of ablation clouds. Charging and rotation of abated clouds were investigated in [P.B. Parks, T. Lu, R. Samulyak, "Charging and ExB rotation of ablation clouds surrounding refueling pellets in hot fusion plasmas", Phys Plasmas 16 (2009) 060705]

- The Lagrangian particle code is an excellent tool for investigation of the influence of various factors on striations

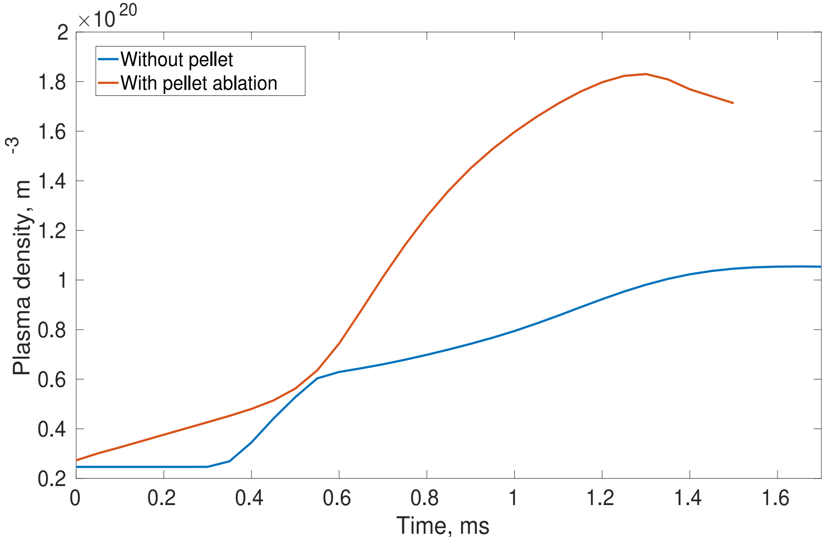
LP simulation of pellet ablation in the presence of plasma perturbations

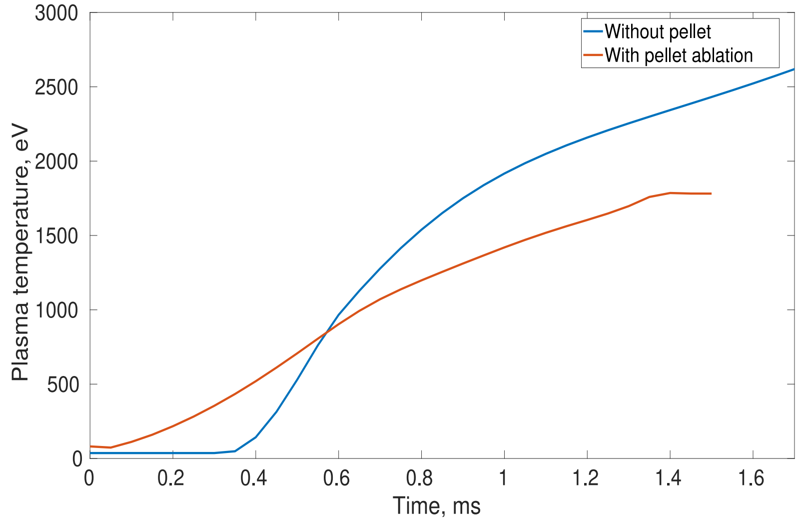


Task II. Problem of background plasma states for pellet ablation.

- Important for all tokamak MHD codes: M3d-C1, NIMROD and JOREK
- MHS codes may use scaling laws with coefficients computed by LP or tabular data sets for the pellet ablation. LP simulates pellet ablation self-consistently.
- All codes need background plasma states (unaffected by ablated plasma) as input into their ablation modules.
- In MHD codes, extracting background plasma states is a difficult problem

Example: Plasma states along the pellet trajectory: comparison of states near ablating pellet with plasma initial conditions.





- Red line: states along the pellet trajectory were obtained from M3D-C1 pellet ablation output data by averaging within 10 cm radius disks around the ablating pellet. Averaging in larger disks to reduce the ablated material influence is not possible as the states become very noisy / unphysical
- Blue line: states along the predicted pellet trajectory were obtained from M3D-C1 initial plasma state before the pellet ablation.

- Assuming the standard scaling law, the ablation rate is 32% higher at 1 ms:

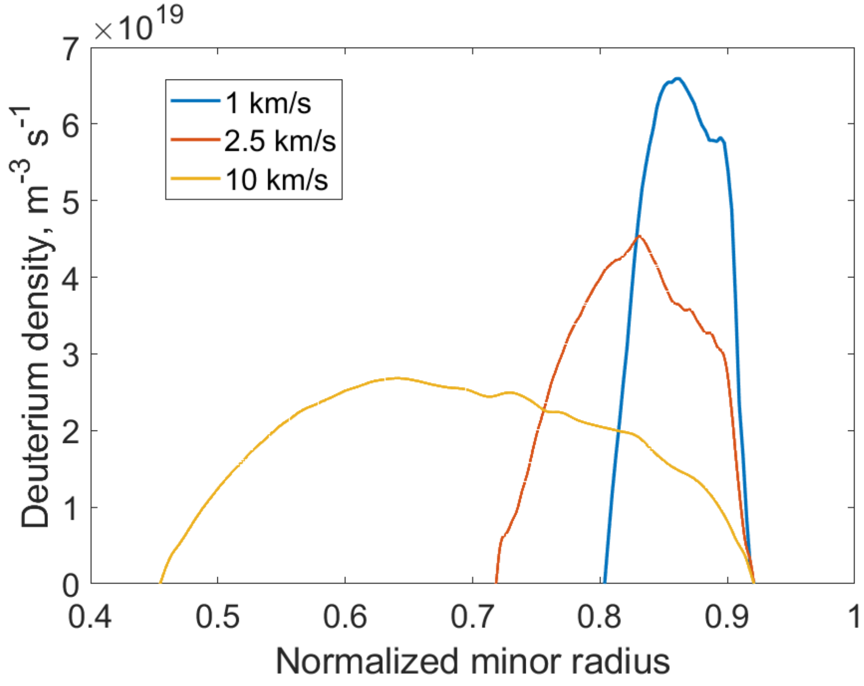
1.7 (increase due to Te) * 0.8 (reduction due to ne) = 1.32

Other problems

Further development of Lagrangian particle pellet code

- Applied math
  - High order (3rd and 4th order) solvers with improved conservation properties
  - Reduced order models and multi-grid-type solvers based on particles

- New physics models
  - Add global tokamak geometry and the magnetic field map to the LP code
  - Improve physics of runaway electrons in the present simulations of SPI (add RE evolution and decay)
  - Improve models for potential distribution in ablation clouds, grad-B drift, Alfven wave drag, external connection (Pegourie) currents drag term etc.



Simulation of fast 3mm radius pellet injected into ITER from LFS. Computing total plasma perturbation density by ablating pellet, shown on the plot, required global magnetic field information, provided by J.MacClenaghan

- Complete study of the pallet ablation scaling laws in magnetic fields in a broad parameter range (short-term goal).
- Perform various pellet fueling and disruption mitigation studies