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Simulation Study of Pellets and SPI Fragments Ablated by Thermal and Runaway Electrons

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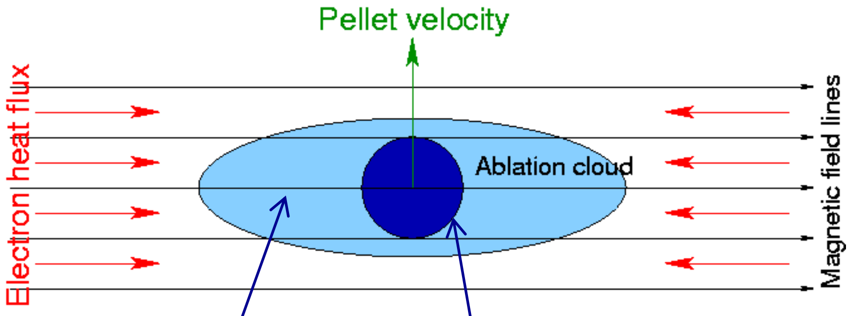
Talk Overview

- Main models and approximation in the Lagrangian Particle code
- Brief summary of recent work on pellet ablation in hot plasmas
- New problem: hydrogen SPI into runaway electron beam in ITER
- Summary and conclusions

Standard models and approximaitons in Lagrangian Particle code



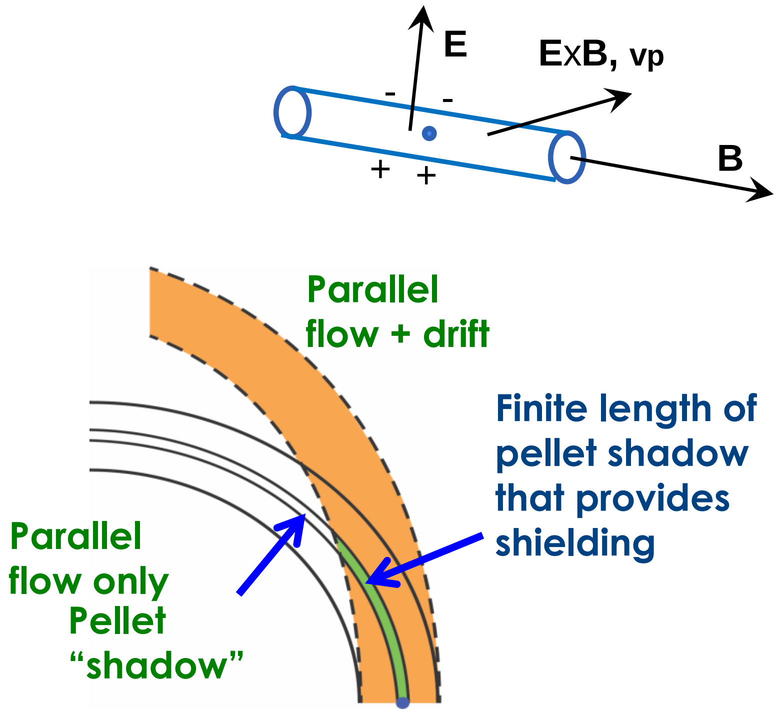
- Phase transition (ablation model) for pellet surface

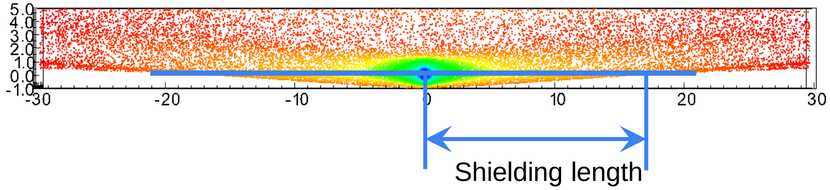
- Low magnetic Re MHD equations
- Kinetic model for the electron heating
- EOS with atomic processes
- Radiation models
- Grad B drift models for ablated material
- Pellet cloud charging models

Lagrangian Particle code **(LP)**

- Highly adaptive 3D particle code, massively parallel
- Lagrangian treatment of ablation material eliminated numerous numerical difficulties associated with ambient plasma, fast time scales etc.
- Supports many SPI fragments in 3D
- LP algorithm: R. Samulyak, X. Wang, H.-S. Chen, J. Comput. Phys., 362 (2018), 1-19.
- LP application to pellets / SPI: R Samulyak, S Yuan, N Naitlho, PB Parks, Nuclear Fusion 61 (4), 046007 (2021).

Transverse flow dynamics in Lagrangian particle pellet code





Polarization ExB drift

- Weakly ionized pellet ablation cloud becomes polarized while traveling across the magnetic field
- ExB force is responsible for the drift of the cloud with the same velocity as the pellet velocity
- In a uniform B field, the flow would extend along the magnetic field line passing through the pellet center, eventually completely shielding the pellet and stopping the ablation
- In older 2D simulations, we assumed that the finite shielding length is an input parameter (estimated as 16 cm)

Grad-B drift

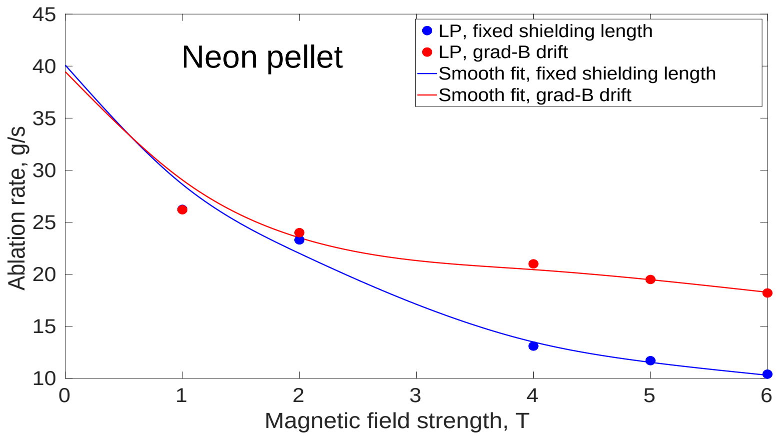
- LP code computes the shielding length self-consistently
- Grad-B drift model. We assume that the electrostatic potential is uniform along each magnetic field line. The equation for the grad-B drift velocity in the large-R direction is

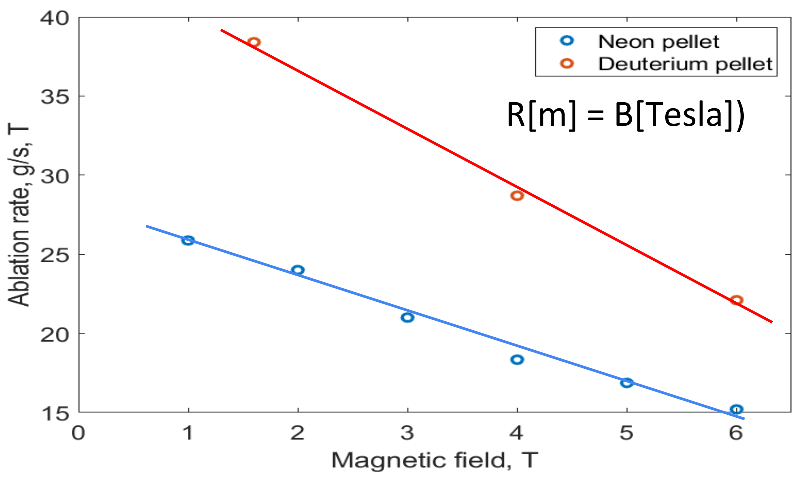
$$\frac{\mathrm{d}v_{\mathrm{D}}}{\mathrm{d}t} = \frac{2\langle P(1+\frac{M_{\parallel}^2}{2}) - P_{\infty}\rangle}{R\langle\rho\rangle} - u_{\mathrm{D}}\frac{2B_{\parallel}^2}{\mu_0 v_{\mathrm{A}}\langle\rho\rangle}$$

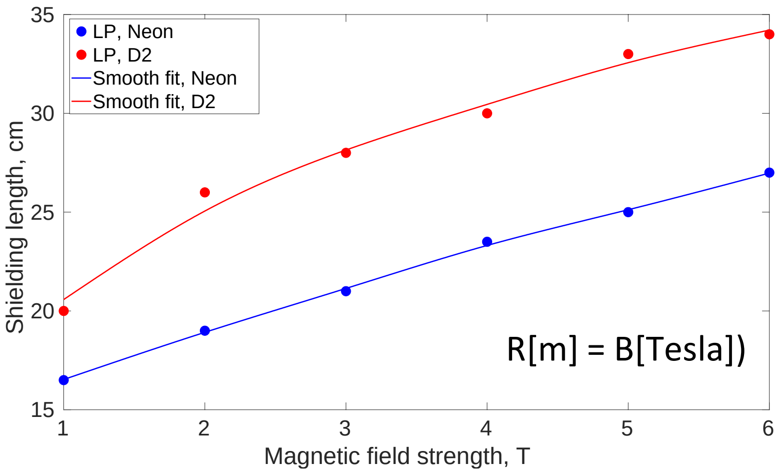
Part I. Pellet ablation by hot plasma electrons

Pellet ablation in magnetic fields ranging from 0 to 6 T with grad-B drift

- In cylindrically symmetric simulations, B field confines the cloud leading to increased density / pellet shielding and reduced ablation rates
- With grad-B drift, the ablation rate is less affected by B field
- One reason is the reduction of the shielding length in magnetic fields
- The main reason: with grad-B drift, the ablated material is not fully confined by magnetic field. It partially drifts across magnetic field, reducing the pellet shielding.
- 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 are computed using this constraint (R[m] = B[Tesla])
- 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.







Scaling laws for pellet ablation rates in magnetic field with grad-B drift

- Scaling laws for the pellet ablation in spherically symmetric approximation are known [Parks, NGS model]

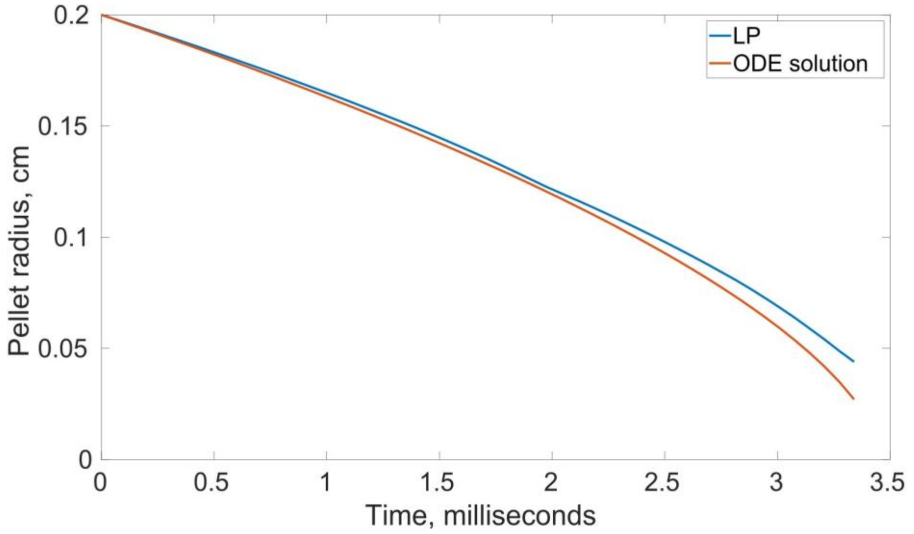
$$G \sim T_{e\infty}^{\frac{5}{3}} n_{e\infty}^{\frac{1}{3}} r_p^{\frac{4}{3}}$$

- We would like to establish scaling laws for the pellet ablation in magnetic fields with grad-B drift
- In our recent work, we showed that **the same scaling law holds for the pellet radius** (see below)
- We observed deviations from the theoretical scaling laws in magnetic fields for changing plasma density and temperature. More work is needed.

- Let's assume that $$G = G_0 \left(\frac{r_p}{r_{p0}} \right)^{\frac{4}{3}}$$

where G_0 is the ablation rate computed for some plasma / magnetic field parameters

- The pellet regression speed is $$\frac{dr_p}{dt} = -\frac{G}{4\pi \rho_0 r_p^2}$$
- This results in the following ODE $$\frac{dr_p}{dt} = -\frac{G_0}{4\pi \rho_0 r_{p0}^{\frac{4}{3}} r_p^{\frac{2}{3}}}$$



- Right plot: analytic ODE solution agrees well with direct numerical simulation of a shrinking pellet.
- Studies of the ablation rate dependence on plasma temperature and pellet radius are in progress

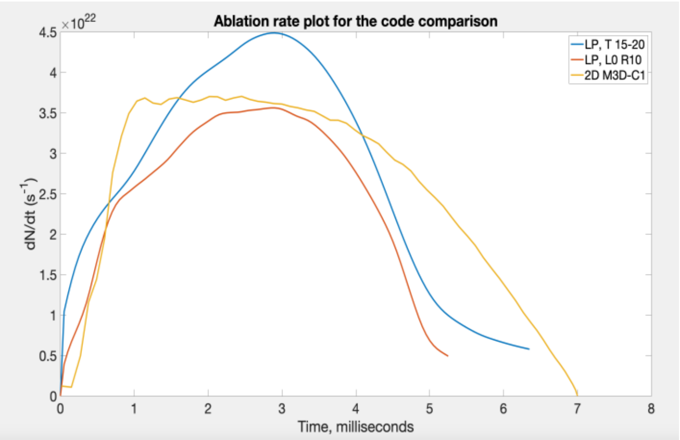
LP simulations using M3D-C1 input (collaboration with B. Lyons, N. Ferraro, S. Jardin)

M3D-C1 simulation in 3D:

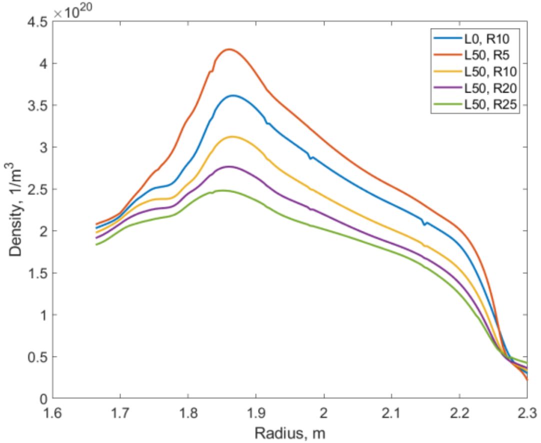
- 1-mm, pure-neon pellet was injected radially inward at Z=0.089 m at 80 m/s (parameters for the extruder given by D. Shiraki).
- The ablated material is deposited in an axisymmetric annulus centered on the pellet with a Gaussian half width 20x the pellet radius (changes over time).

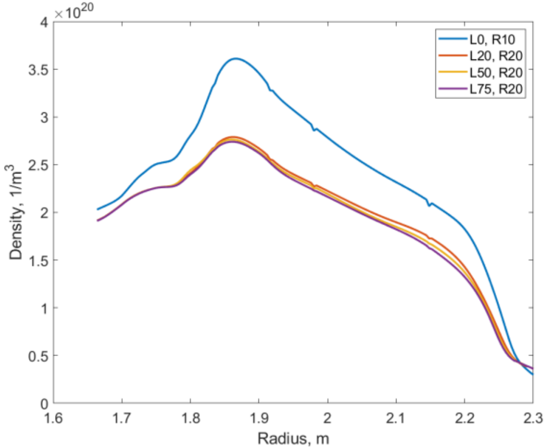
Lagrangian Particle simulation:

- We examined the sensitivity of plasma states in M3d-C1 simulation to the location and size of the averaging domain
- Using ne(t), Te(t), B(t) near the ablating pellet (but not affected by the analytic source term) we performed LP simulations and compared ablation rates with M3d-C1 and analytic scaling laws



An additional test was performed to check if LP agrees with M3D-C1 if plasma states are averaged in 10 cm disk at pellet location (red line)

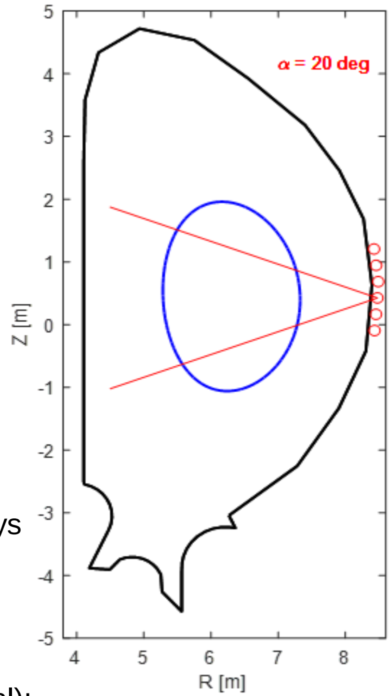




Labels L N1, R N2 mean that plasma states were averaged in R=N2(cm) radius disk at L = N1 (cm) distance from the pellet in both directions

- Density and Temperature are very sensitive to the disk radius and not sensitive to the longitudinal displacements. B field is not sensitive
- Blue line, averaging in 10 cm radius disk at the pellet location, was added for the reference

Part II: SPI into a Runaway Electron (RE) Beam Introduction.



RE beam parameters

- Minor radius of 1 m and elongation of about 1.5 with the position as indicated in the figure;
- 1 MA and 10 MA of runaway current
- E_{RE} = 20 MeV mono-energetic
- Uniform density of $n_{RE} = 5\text{x}10^{15}$ m^{-3} (1MA) or $5\text{x}10^{16}$ m^{-3} (10 MA)

Companion plasma parameters

- Plasma temperature: 20 eV
- D density: $1\text{x}10^{20}$ m^{-3}, Ne density: $5\text{x}10^{19}$ m^{-3} (corresponds to pure Ne injection resulting in 50 ms CQ time);
- Electron densities based on coronal equilibrium ionization stages not considering ionization through runaways $3\text{x}10^{20}$ m^{-3} (20 eV).

SPI parameters

- Large hydrogen pellet, diameter D=28.5mm, length L=57mm, velocity = 500 m/s (fragment velocity identical);
- The velocity dispersion of the fragments is dv/v = 0.4 resulting in an approximate injection duration of 2.2 ms at the edge of the RE beam;
- Mono-sized fragments are considered. In particular, we we used the folowing number and diameter of spherical fragments for a single pellet: **555 (5 mm), 69 (10 mm)**.

RE-related Physics models added to the LP Code

- **Volumetric heating by runaway electron beams:**

$$\frac{d}{dt}\frac{e_{RE}}{m_e c^2} = -4\pi r_e^2 c \ln \Lambda_{free} \left(n_{free} + \frac{1}{2} n_{bound}\right)$$

- **Parallel heat conduction** (minor effect on numerical results):

$$\rho c_p T_t = k_{\|} T_{xx}$$

where $k_{\|} = k_0 T_e^{\frac{5}{2}}$, $k_0 = \frac{3.292 \times 10^5 \lambda_T}{Z \ln \Lambda}$, $\lambda_T = \frac{0.4Z}{3.24 + Z + 0.3888 \ln Z}$

- **Impact ionization of the ablated cloud by runaway electrons:** (impact ionization rates courtesy N. Garland)

$$R = N_e \int v\sigma(E) f_e(E) dE$$

$$f_i = Rt$$

Part II (a): Single pellet fragment in RE beam in ITER

- An ablated cloud of a single fragment undergoes a longitudinal expansion driven by runaway electron heating and transverse dynamics driven by ExB and grad-B drifts.

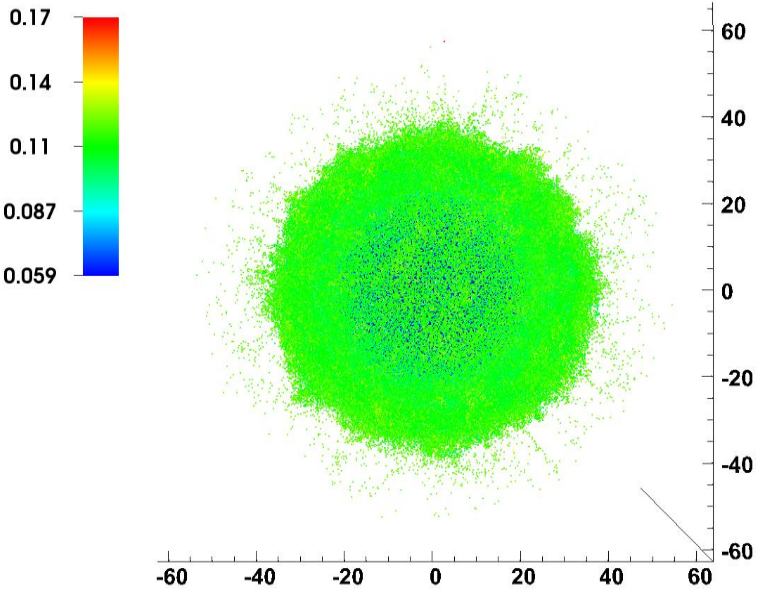
- The longitudinal dynamics is studied first (the transverse dynamics is ignored). We consider the effects of thermal Saha cloud ionization and the impact ionization by runaway electrons, and thermal conductivity. We also simulation long-scale longitudinal dynamics by of multiple passes of the ablation cloud in ITER.

- Then we focus on the transverse dynamics of the single fragment ablation cloud driven by ExB and grad-B drifts.

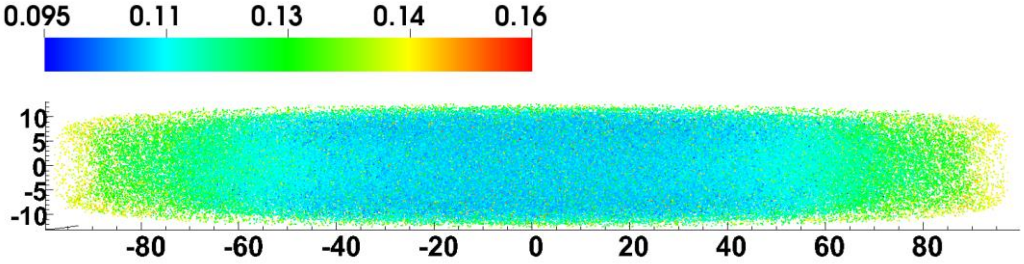
- A single 10 mm diameter fragment is considered. The background plasma has 20 eV temperature and other parameters as described in Introduction. Details of the ablation phase transition are neglected: we assume that the fragment was instantaneously vaporized. The initial fragment state is gas with the density of solid hydrogen. We verified that cloud dynamics is not sensitive to some pressure / temperature variations in the initial states. The pellet rocket effect is within code capabilities and will be investigated in the future.

Longitudinal cloud expansion in 1 MA RE current (transverse dynamics ignored). Influence of thermal and impact ionization

Thermal (Saha) ionization: the expansion of the cloud is spherical and no MHD effects are observed Thermal ionization in the bulk of the cloud ~ 1e-7.



Electron impact + thermal ionization: After adding the electron ionization by impact with ionization rate R = 20.8 1/s, we observe significant MHD effects in the cloud and the channeling of the ablated material around ITER. The total ionization in the bulk of the cloud becomes 0.004 and the cloud expansion reaches ± 95 cm after t = 200 microseconds.

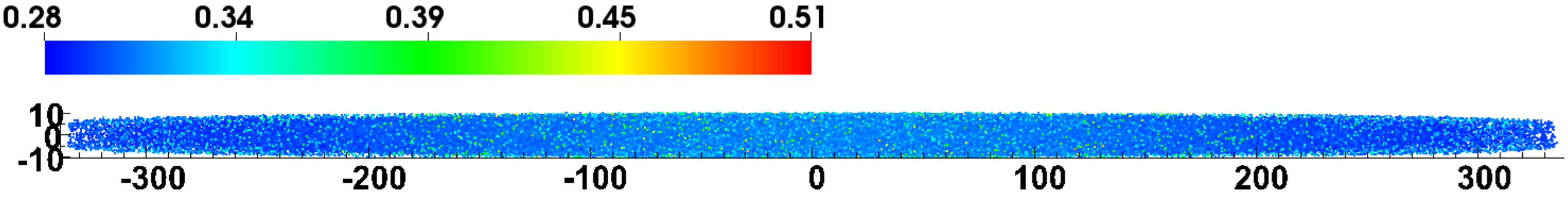


Longiudinal cloud expansion expansion with thermal and impact ionization in 10 MA RE current. Transverse dynamics ignored.

- When the RE current is increased to 10 MA, the heating of the cloud and the thermal ionization alone is enough to channel the cloud along magnetic field. However, the expansion of the cloud is much slower as compared to the simulation with ionization by impact, R = 208 1/s.

Cloud expansion at t = 200 microseconds:

- **Saha ionization**: ± 160 cm in the longitudinal direction, channel radius = 20 cm
- **Impact + thermal ionization**: ± 330 cm, channel radius = 10 cm, as shown in the image below

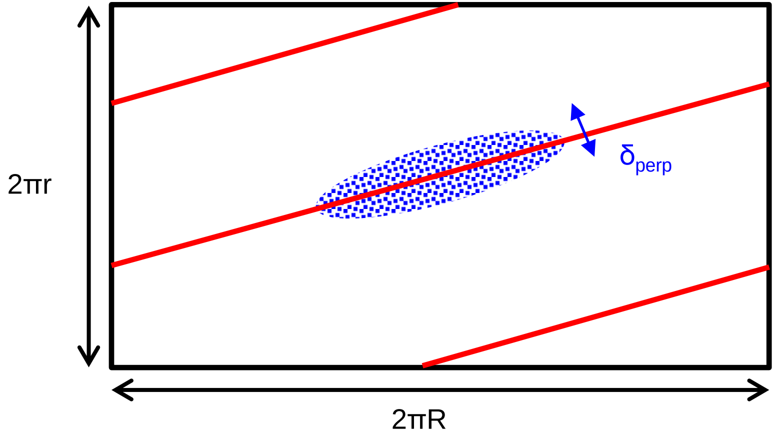


Temperature distribution of hydrogen pellet hit with 10 MA RE beam, thermal ionization + ionization by impact

Large-scale longitudinal dynamics in 10 MA RE beam: two 'extreme' cases

Short connection length

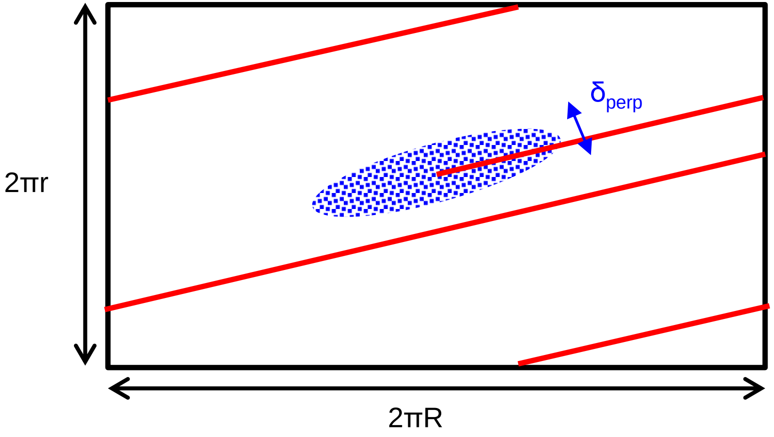
$q = 2$



- A magnetic field line closes after two toroidal turns
- δ_{perp} ≡ transverse dimension of ablation cloud

Long connection length

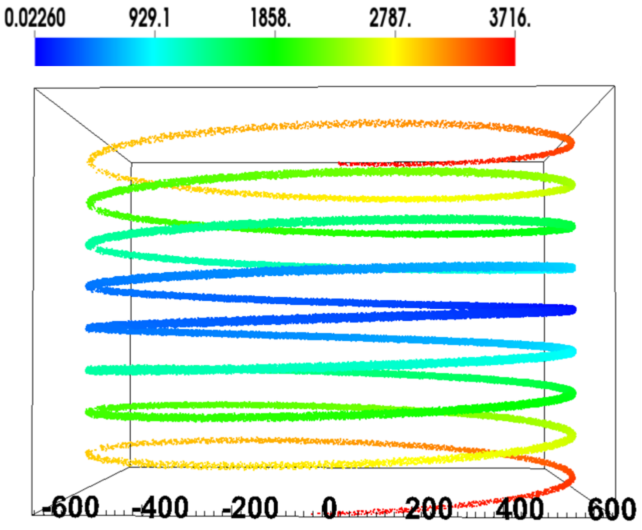
$q = 2 + \varepsilon$

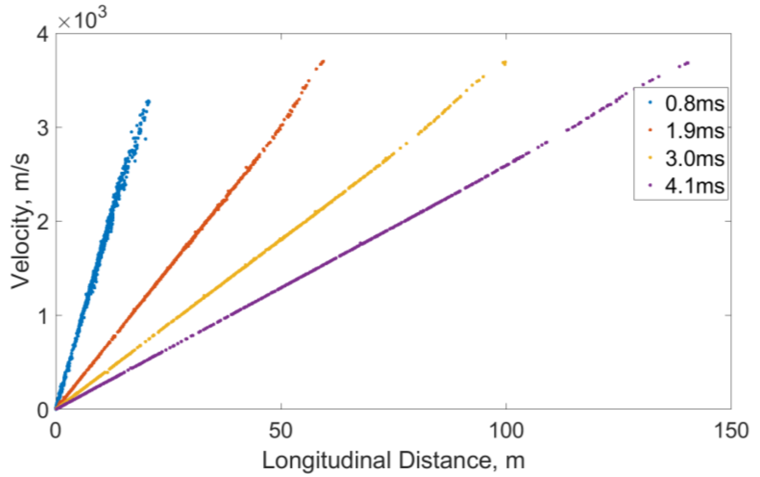


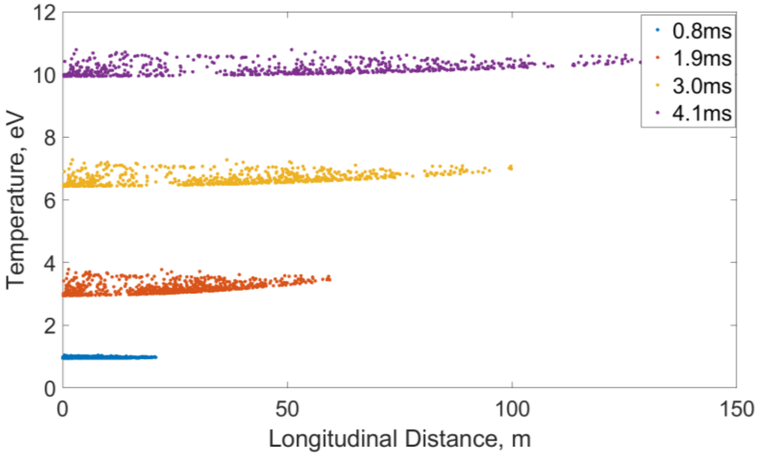
ε is such that the magnetic field line just misses the ablation cloud after 2 toroidal turns, i.e. $\varepsilon = \delta_{perp}/(2\pi r)$

Large-scale dynamics for long connection length, q = 2 + ε

The computational domain in the longitudinal direction was set to one circumference of the ITER = 40 m. After the material reaches the end of the domain, we apply periodic boundary conditions. At t = 5 milliseconds, the cloud spirals 9 times around the tokamak.



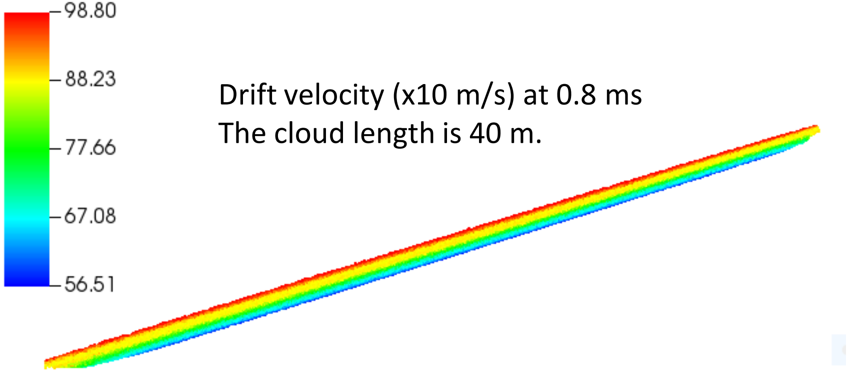




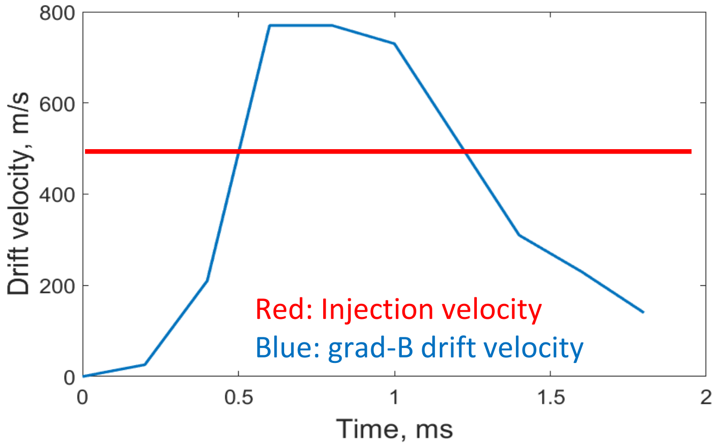
Left plot: 3D velocity distribution of hydrogen pellet cloud in 10 MA RE beam

Right plots: distribution of states along the ablatiton cloud

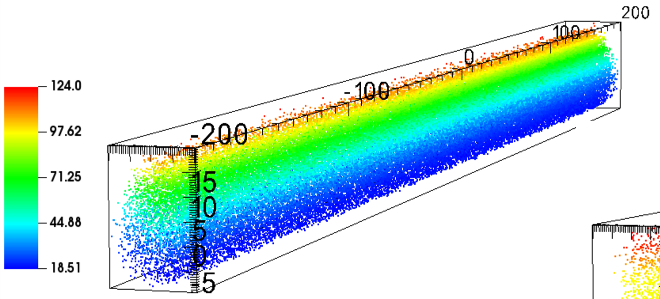
Transverse dymaics of single fragment cloud in 10 MA RE beam



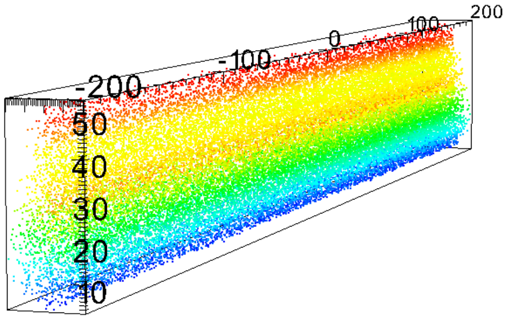
Drift velocity (x10 m/s) at 0.8 ms
The cloud length is 40 m.



Slice of the cloud at 0.5 ms



Slice of the cloud at 0.8 ms

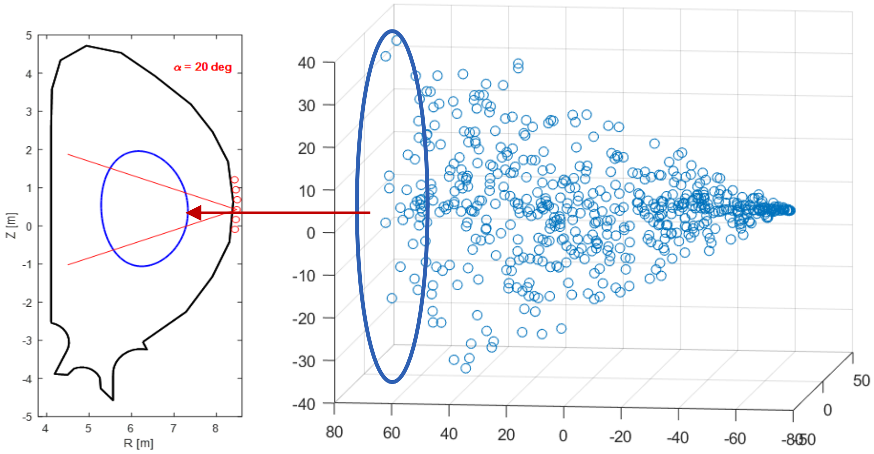


- Large grad-B drift velocity builds up during the first 0.6 ms and the penetration stops
- The grad-B drift quickly reduces after 1 ms because the pressure in the cloud drops, and the Mach number effect is also small: the max velocity is almost constant while T increases.
- The total penetration is of the order of fragment cloud diameter
- The overall result is close to ablating the pellet fragment at the edge of the RE region

Part II (b): SPI in RE beam in ITER

- SPI fragments are injected into the RE region using random distribution within the injection time. The velocity magnitude of all fragments is the same (500 m/s), but the velocity direction is random within the velocity cone (dv/v = 0.4)

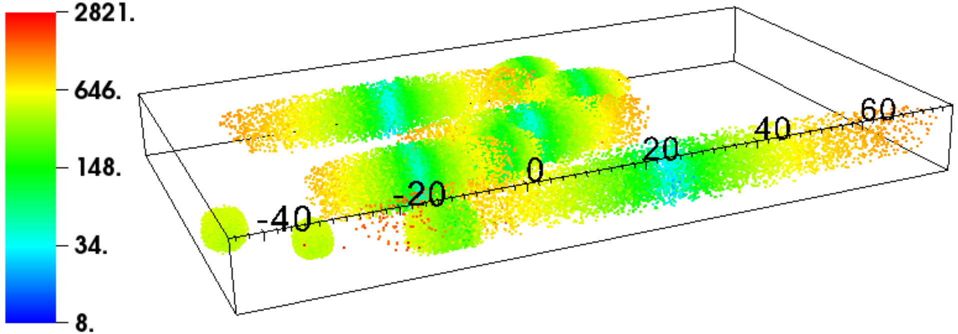
- Example: distribution of 555 fragments. As fragments enter the RE region, they become ablated by eigher 10 MA RE current



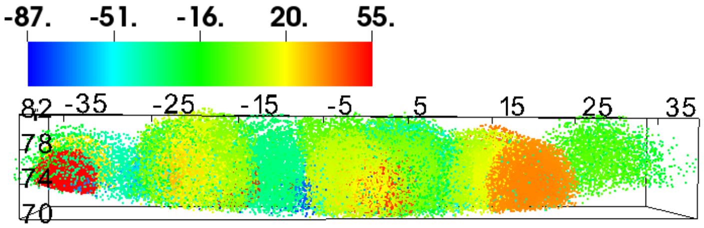
- 69 fragments of 10 mm in diameter and 555 fragments of 5 mm in diameter were usedin current study
- The background plasma: T = 20 eV and other are as parameters descrived in the introduction slide
- Two cases considered:

1. Ablated fragment clouds ExB drift with their original velocity and grad-B drift in the direction of large radius
2. For comparison, we show simulations with drift forces excluded (pellets deposit their material at the edge of the ablation cloud

555 SPI fragments in 10 MA RE beam current (ExB and grad-B drifts are included)

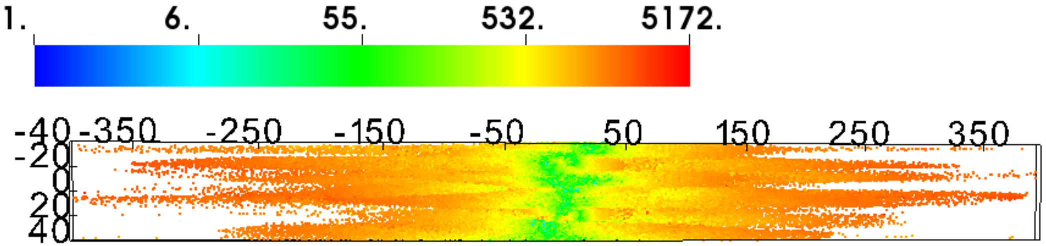


Initial stage of SPI: first fragments enter the RE region and the ablation starts. Injection direction is vertically up.



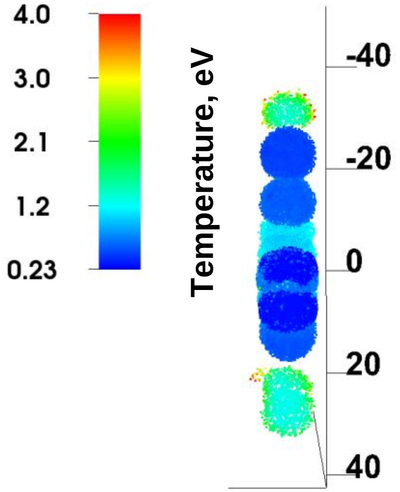
View in the direction of magnetic field line at 1.5 ms. Injection direction is vertically up.

View in the injection direction at 1.5 ms

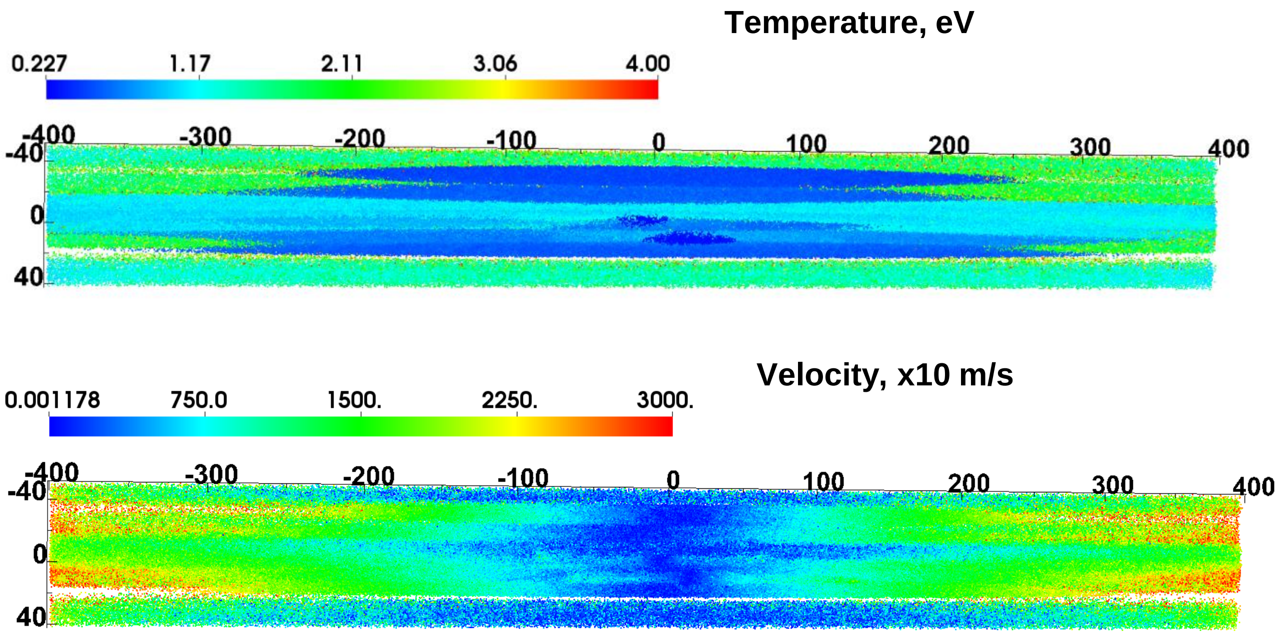


- The penetration depth is on the order of the fragment cloud diameter
- After the ablation cloud of each fragment expands to ~ 7 m, grad-B drift moves the coud in the direction opposite to the injection away from the RE region
- In the right plots, we show only particles located in the RE region
- The RE region had a step function profile in the present simulations

69 SPI fragments in 10 MA RE beam current (no transverse drift)



View in the direction of magnetic field line



View in the injection direction

- For comparison, we presented a simulation of SPI with no transverse drift
- New fragments deposit their material into the same ablation cloud layer
- The ablated material remains in the RE region: no grad-B drift in the direction opposite to the injection

Conclusions

Pellets ablated by hot thermal electrons

- Performed studies of the neon and deuterium pellet ablation in magnetic fields ranging from 1 to 6 T with grad-B drift. Showed that grad-B drift makes the ablation rate less sensitive to the magnetic field compared to cylindrically symmetric simulations.
- Showed that the theoretical scaling law for ablation rates in spherical geometry for changing pellet radius holds in magnetic fields (at least for small pellets). We observed deviations from the theoretical scaling laws in magnetic fields for changing plasma density and temperature. More work is needed.
- Performed simulations of the pellet ablation at changing plasma conditions using input from M3D-C1

SPI in runaway electron beams

- Performed simulations of a single 10 mm diameter fragment injected into the runaway electron beam in ITER. Studied the influence of thermal and electron impact ionization mechanisms and thermal conduction of the dynamics of ablated clouds in ITER.
- Showed that grad-B drift limits the penetration into the RE region. The penetration depth is on the order of the cloud diameter.

- SPI consisting of 555 fragments of 5 mm in diameter were studied in 10 MA RE current. The process is strongly dependent on the grad-B drift. After the ablation cloud of each fragment expands to ~ 7 m, grad-B drift moves the coud in the direction opposite to the injection away from the RE region.

Future work

Pellet ablated by hot thermal electrons

- Complete work on scaling laws for ablation rates in magnetic field
- Pellet simulation database: G(rp, B, Te, ne) at B[T] = R[m]
- Continue joint work with M3D-C1

SPI in runaway electron beams

- Realistic profiles for runaway electron density distribution
- Long scale dynamics of the ablated material in tokamaks
- More detailed study of the initial phase of fragment ablation: phase transition process, non-uniform states along the pellet surface resulting in the rocket effect