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Lagrangian Particle Simulation of Hydrogen Pellets and SPI into Runaway Electron Beam in ITER

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Abstract

Numerical studies of the ablation of hydrogen pellets and shuttered pellet injection (SPI) fragments into a runaway electron beam in ITER have been performed using the time-dependent pellet ablation code [R. Samulyak at el., Nucl. Fusion, 61 (4), 046007 (2021)] based on Lagrangian Particle (LP) method. The code implements low magnetic Reynolds number MHD equations, volumetric heating by runaway electrons, an equation of state with multiple ionization, an ionization by impact model, and a model for grad B drift of the ionized material across the magnetic field. The study of the single fragment ablation quantifies the influence of various factors, in particular the impact ionization by runaway electrons and various cross-field drift terms on long-scale dynamics of the ablated plasma. We show that the grad-B drift prevents the ablated material from penetration deeply into the runaway region. Simulations of the SPI at various numbers of pellet fragments provide information on global dynamics of the ablated plasma and the penetration depth into the runaway region.

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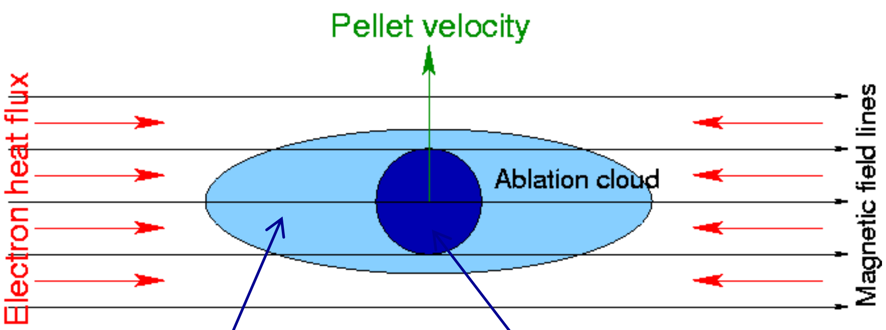
Near-field models and software for pellet (SPI) ablation

Pellet / SPI fragment ablation is intrinsically a multiscale problem with scales ranging from sub-millimeter layers near solid surfaces to tokamak size. The pellet ablation rate strongly depends on the resolution of processes on and near the pellet surface. The LP code was developed for this purpose.



- Phase transition (ablation model) for pellet surface or volumetric pellet heating model

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

Lagrangian Particle code

- Highly adaptive 3D particle code, massively parallel
- Lagrangian treatment of ablation material eliminated numerical difficulties associated with ambient plasma, fast time scales etc.
- Supports large number of 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).

Current applications:

- Simulation of single pellet ablation and SPI (DIII-D neon pellets experiments)
- Studies of scaling laws for pellet ablation
- Simulation of hydrogen SPI into runaway electron beam

Governing equations: MHD equations in Low Magnetic Reynolds Number Approximation

- The ablation cloud expansion is governed by the inviscid, compressible Euler's equations with electromagnetic terms:

$$\frac{d\rho}{dt} = -\rho\nabla\mathbf{u},$$
$$\rho\frac{d\mathbf{u}}{dt} = -\nabla P + \mathbf{J}\times\mathbf{B},$$
$$\rho\frac{de}{dt} = -P\nabla\cdot\mathbf{u} + \frac{1}{\sigma}\mathbf{J}^2 + Q_{RE},$$
$$P = P(\rho, e),$$

- Current density from Ohm's Law: $\mathbf{J} = \sigma(-\nabla\phi + \mathbf{u}\times\mathbf{B})$

- In this work, we assume that the ablation cloud is uniformly charged by the incoming plasma electrons and runaway electrons, resulting in a constant value of the the electric potential.

- Volumetric heating source term due to runaway electrons: $Q_{RE} = 4\pi m_e r_e^2 c^3 n_{RE} \ln\Lambda_{free}(n_{free} + \frac{1}{2}n_{bound})$

B. Breizman et al. Nuclear Fusion, 59(8):083001, 2019.

Equation of State with Saha ionization model and ionization by impact

- **Saha LTE EOS for hydrogen:**

$$\frac{f_i^2}{1-f_i} = 3.0\times 10^{21}\frac{T^{\alpha_i}}{n_t}exp(-\frac{\epsilon_i}{T})$$

$$\frac{f_d^2}{1-f_d} = 1.55\times 10^{24}\frac{T^{\alpha_d}}{n_t}exp(-\frac{\epsilon_d}{T})$$

, where $\alpha_i = \frac{3}{2}$ and $\alpha_d = 0.327$.

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

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

$$f_i = Rt$$

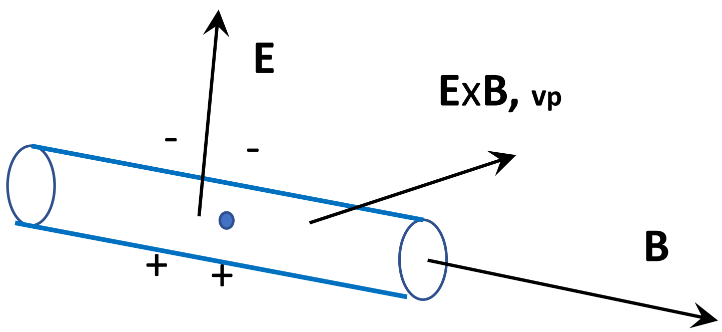
where $\sigma(E)$ is the collision cross-section, f_e is the electron energy distribution

RE density/energy	1 MeV	5 MeV	10 MeV	20 MeV	30 MeV
$5\times 10^{15}\ m^{-3}$ [1 MA]	10.69	17.43	19.15	20.88	21.91
$1\times 10^{16}\ m^{-3}$	21.39	34.86	38.29	41.77	43.82
$5\times 10^{16}\ m^{-3}$ [10 MA]	106.93	174.29	191.46	208.83	219.09
$1\times 10^{17}\ m^{-3}$	213.87	348.57	382.91	417.67	438.18

- **Transverse electric conductivity model:**

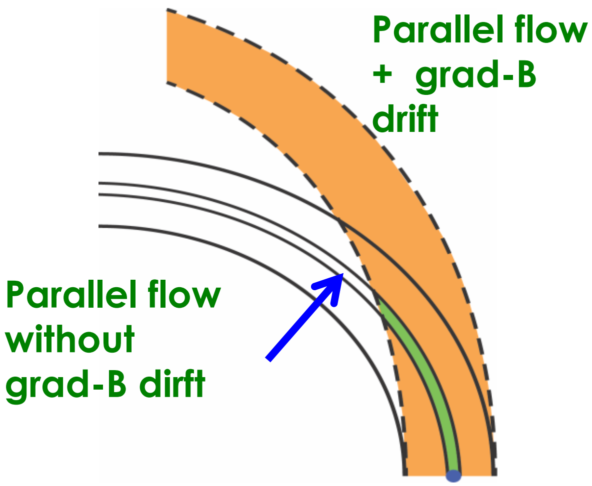
$$\sigma\left[\frac{\Omega}{\mathrm{m}}\right] = \frac{9.675\times 10^3}{\ln\Lambda T_e[\mathrm{eV}]^{-3/2} + 0.054 T_e[\mathrm{eV}]^{-0.059}(1/f_i - 1)},$$

Transverse flow dynamics in 3D Lagrangian particle pellet code



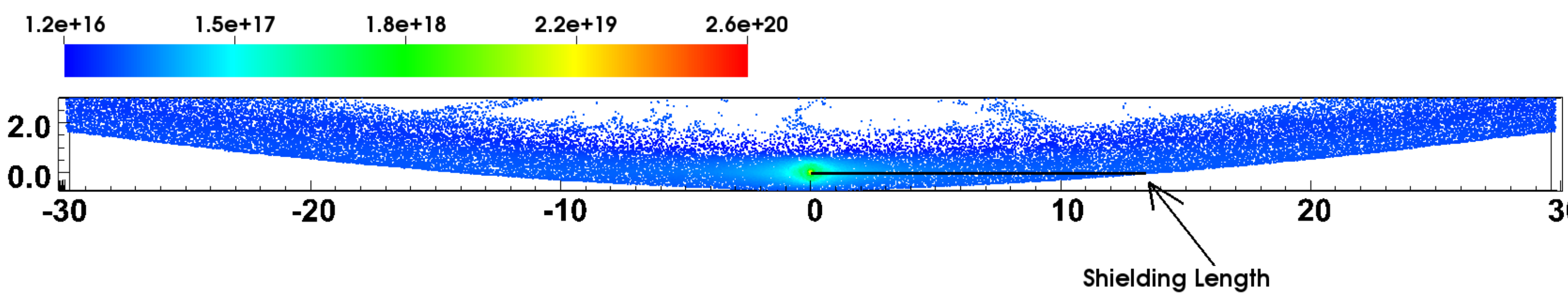
Polarization ExB drift

- 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 injection velocity



Grad-B drift

- Grad-B drift (polarization E x B drift due to the curvature of magnetic field lines) self-consistently establishes the shielding length of the ablation cloud



Improved drift model accounting for internal and external (Pegourie) connection currents

$$n_0 m_0 \frac{dV_d}{dt} = \frac{1}{1+\left(1-P_{Alf}-P_{con}\right)\left(L'_{con} n_\infty m_\infty / Z_0 n_0 m_0\right)} \times$$

$$\left[\frac{2\left[\left(p_0^e + p_0^i\right)\left(1+M^2/2\right) - \left(p_\infty^e + p_\infty^i\right)\right]}{R} \frac{qR}{Z_0} \sin\left(\frac{Z_0}{qR}\right) - \frac{V_d B_\infty^2}{Z_0} \times \left\{ P_{Alf} \frac{2H\left(f_0^i - f_c^i\right)}{\mu_0 C_A} + P_{con} \frac{\left[1-e^{-t/\left(\tau_{coll}^e+\tau_L\right)}\right]\pi R_0^2 \sigma_\infty}{L_{con}} \right\} \right]$$

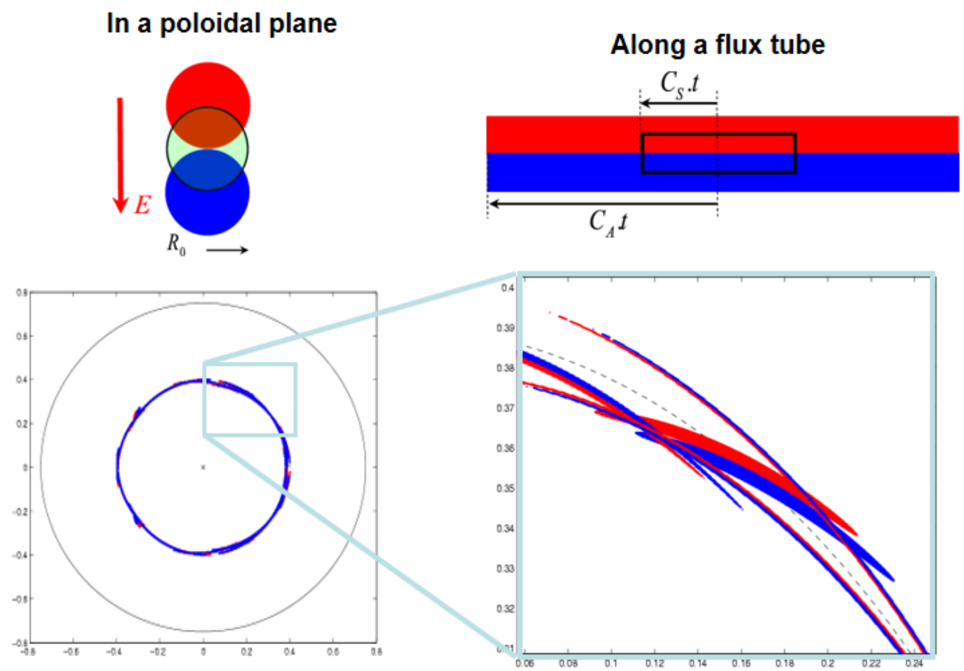
Violet term: grad-B grift

Blue term: positively and negatively charged parts of the cloud are connected, and parallel (Pegourie) current can flow.

Red term: Alfven wave drag (no self connection)

Green term: positively and negatively charged parts of the cloud are connected by the same polarity – no currents

Brown term: internal connection currents



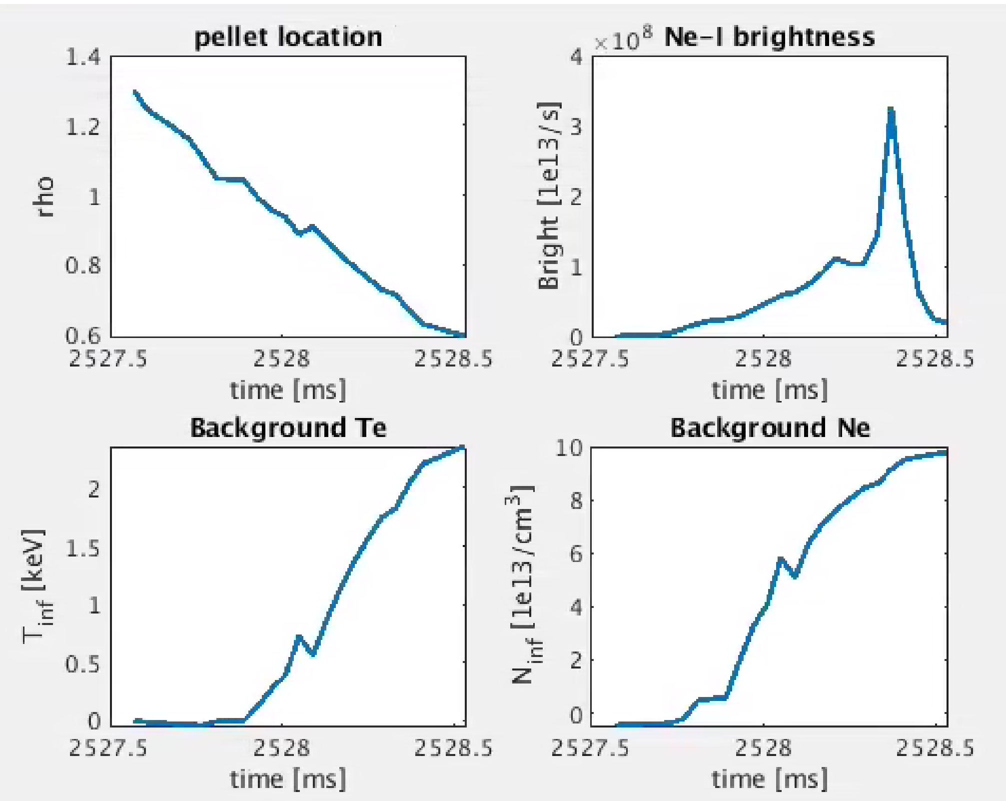
After $C_A t$ = 7 toroidal turns in each direction (few 10 × µs)

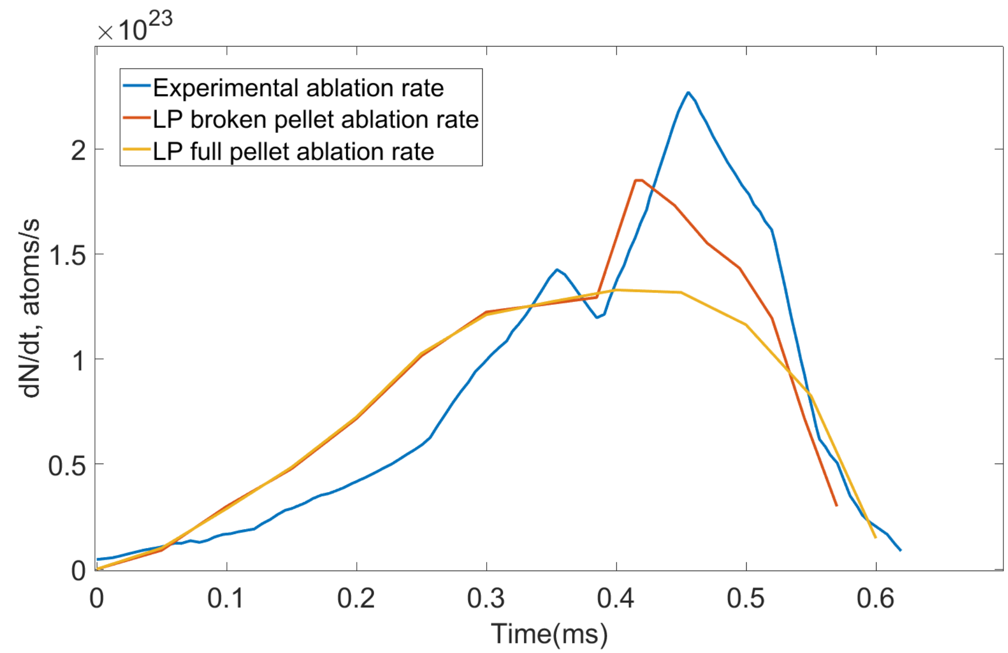
P_{con} (P_{Alf}): Proportion of cloud self-connected (+ vs. -) (NOT self-connected) at time t

L_{con} : Harmonic average of the length of the field lines self-connecting the plasmoid [m]

Recent LP validation results against DIII-D neon pellet experiments

Experiment injected small (~1.3mm diameter) frozen pellets into DIII-D Super-H target plasma. (Experimental data courtesy Eric Hollmann, private communication)





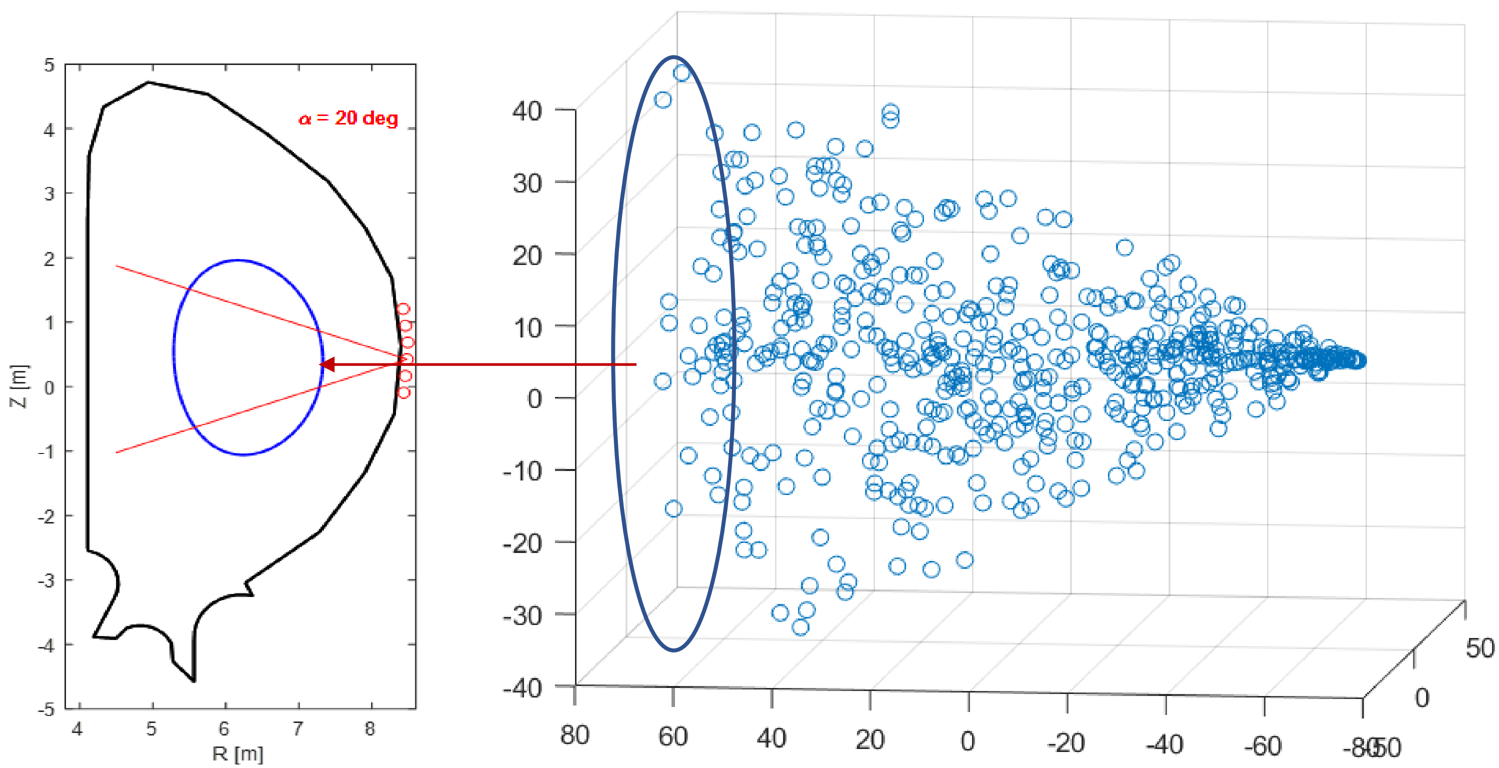
The spike in experimental data at t=0.5ms was either due to the plasma instability or the pellet breaking up (separation of fragments). The LP code simulates the pellet breaking up into two same-sized pieces at 0.4ms (red curve).

LP simulation of ablation rates of deuterium pellets are also in good agreement with past experiments.

SPI into RE beam in ITER: problem setup

- SPI fragments are injected into the RE region using random distribution within the injection time. The velocity magnitude of the unshattered pellet is v=500m/s. The shattering process generates a velocity dispersion of dv/v=0.4

- As fragments enter the RE region, they are ablated by the RE beam with maximum current of10 MA



RE beam parameters and plasma states

RE beam parameters

- Minor radius of 1 m and elongation of about 1.5m
- 1 MA and 10 MA of runaway current
- E_{RE} = 20 MeV mono-energetic
- Electron density of $n_{RE} = 5x10^{15}\ m^{-3}$ (1MA) or $5x10^{16}\ m^{-3}$ (10 MA)

Background plasma parameters

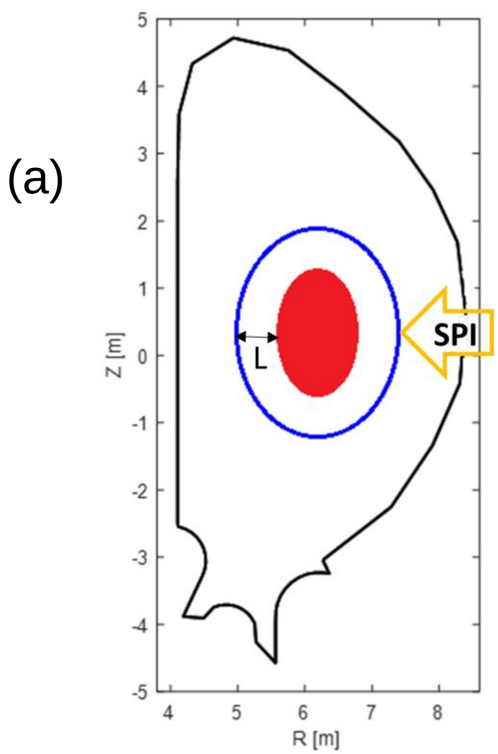
- Plasma temperature considered: 20 eV
- D density: $1x10^{20}\ m^{-3}$, Ne density: $5x10^{19}\ m^{-3}$ (relevant to pure Ne injection resulting in 50ms CQ time);
- Electron densities based on coronal equilibrium ionization $3x10^{20}\ m^{-3}$ (20 eV).

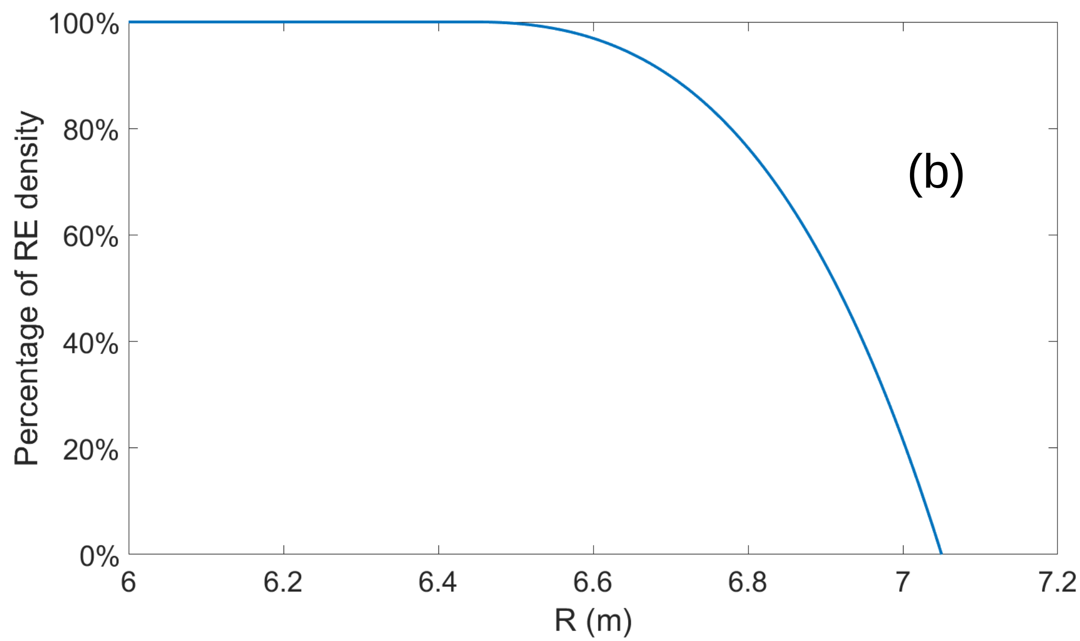
SPI parameters

- Large hydrogen pellet, diameter D=28.5mm, length L=57mm, velocity = 500 m/s
- 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;
- Various numbers (500 - 5000) of mono-sized fragments considered

Implementation of RE beam profile

In our simulations, we approximate the geometry of the transverse section of RE beam as an ellipse with the length of the semi-major axis 1.5 m and the semi-minor axis 1.05 m. The RE beam intensity has a ramp outside the core area.





(a) Schematic of the RE beam in ITER. The RE region is indicated by the blue curve. The red ellipse represents the core area and the space between the core and the edge is a ramp with thickness L = 60cm. SPI fragments are injected from right to left. (b) Profile of the relative RE density from the ramp edge to the tokamak center (the core density is taken as 100%).

Part I: Single pellet in RE beam in ITER

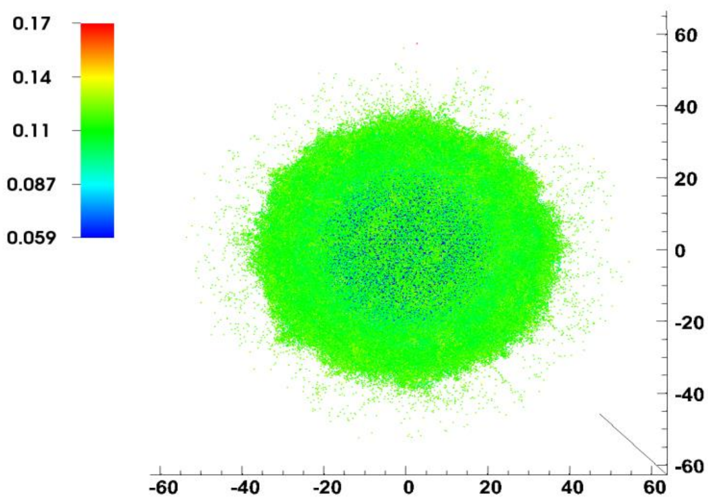
- A single 5 mm diameter fragment is injected into the runaway electron beam in ITER, 20 eV background plasma T
- **Goals of the single pellet study:**
  - Clarification of ionization of impact on ablation cloud dynamics
  - Clarification of the relative magnitude of cross-field transport terms
  - Determining the penetration depth of the cloud into the RE beam and long-scale dynamics

Effect of impact ionization on cloud expansion with 1MA Re current (simplified setting with grad-B drift excluded)

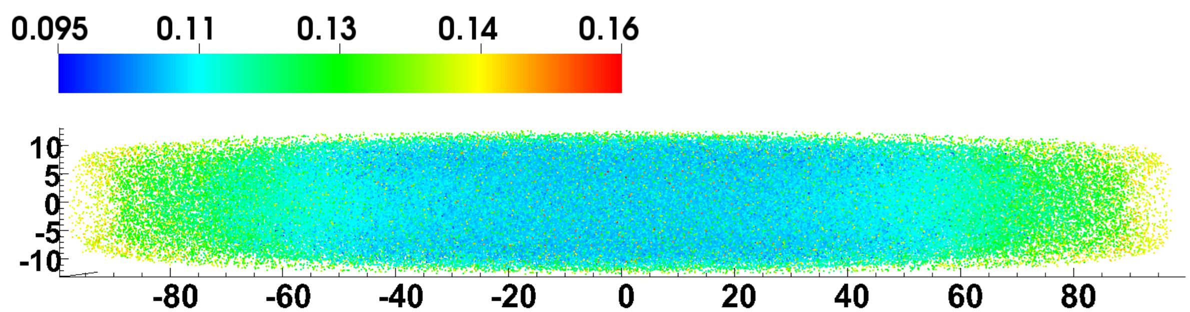
Thermal (Saha) ionization only: the expansion of the cloud is spherical and no MHD effects are observed Thermal ionization in the bulk of the cloud ~ 1e-7.

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.

Temperature (eV)



Temperature (eV)



cm

10 MA RE current: cloud expansion with thermal and impact ionization

- 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.

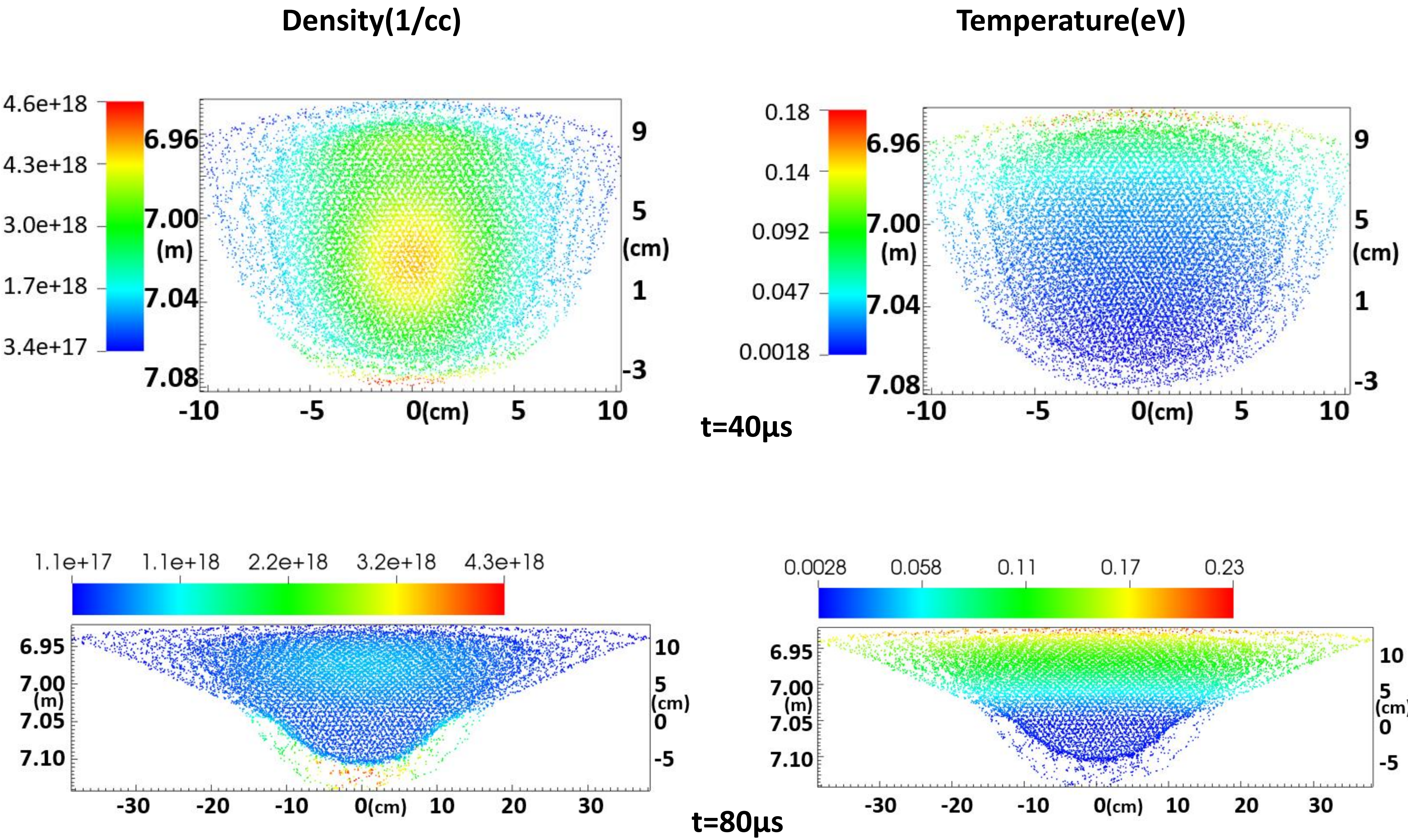
Cloud expansion at t = 200 microseconds:

- **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

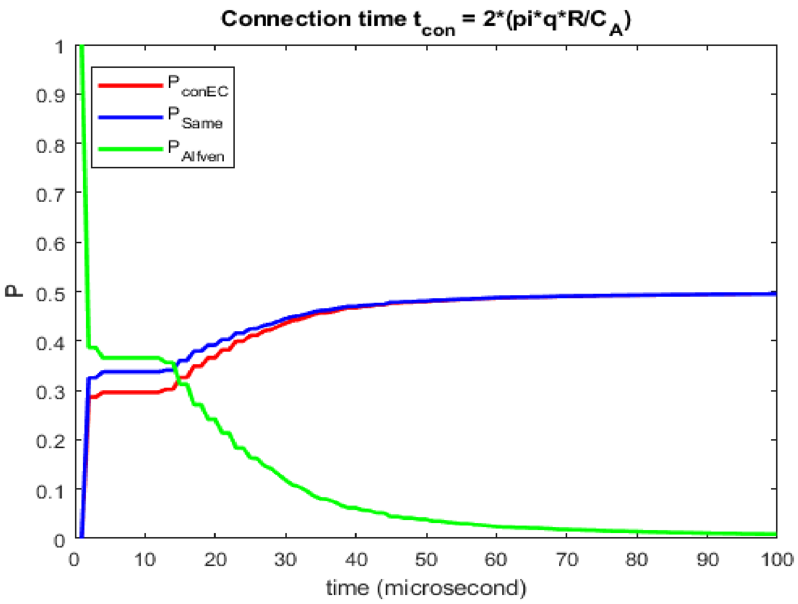
Conclusions:

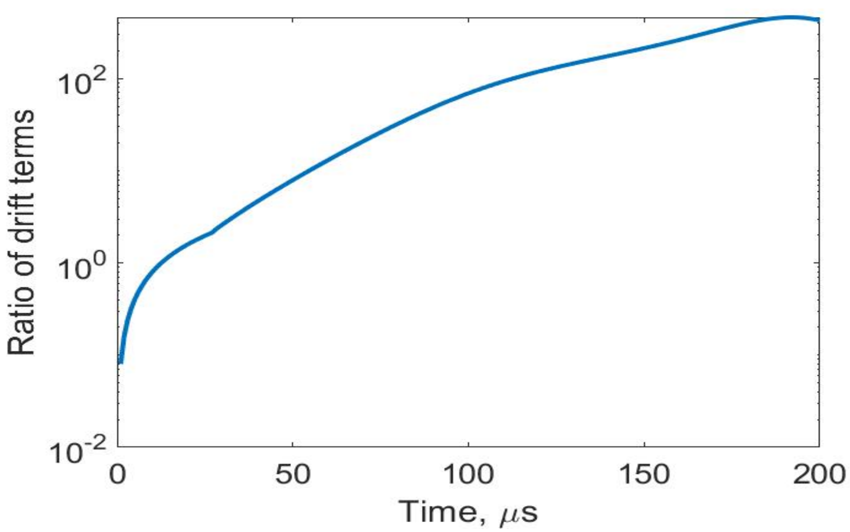
- Impact ionization has a significant effect on the ablation cloud dynamics at lower runaway beam densities
- Using impact ionization is very important in the RE beam ramp region

Single pellet injection into RE beam through the ramp. Early stages of ablation cloud evolution



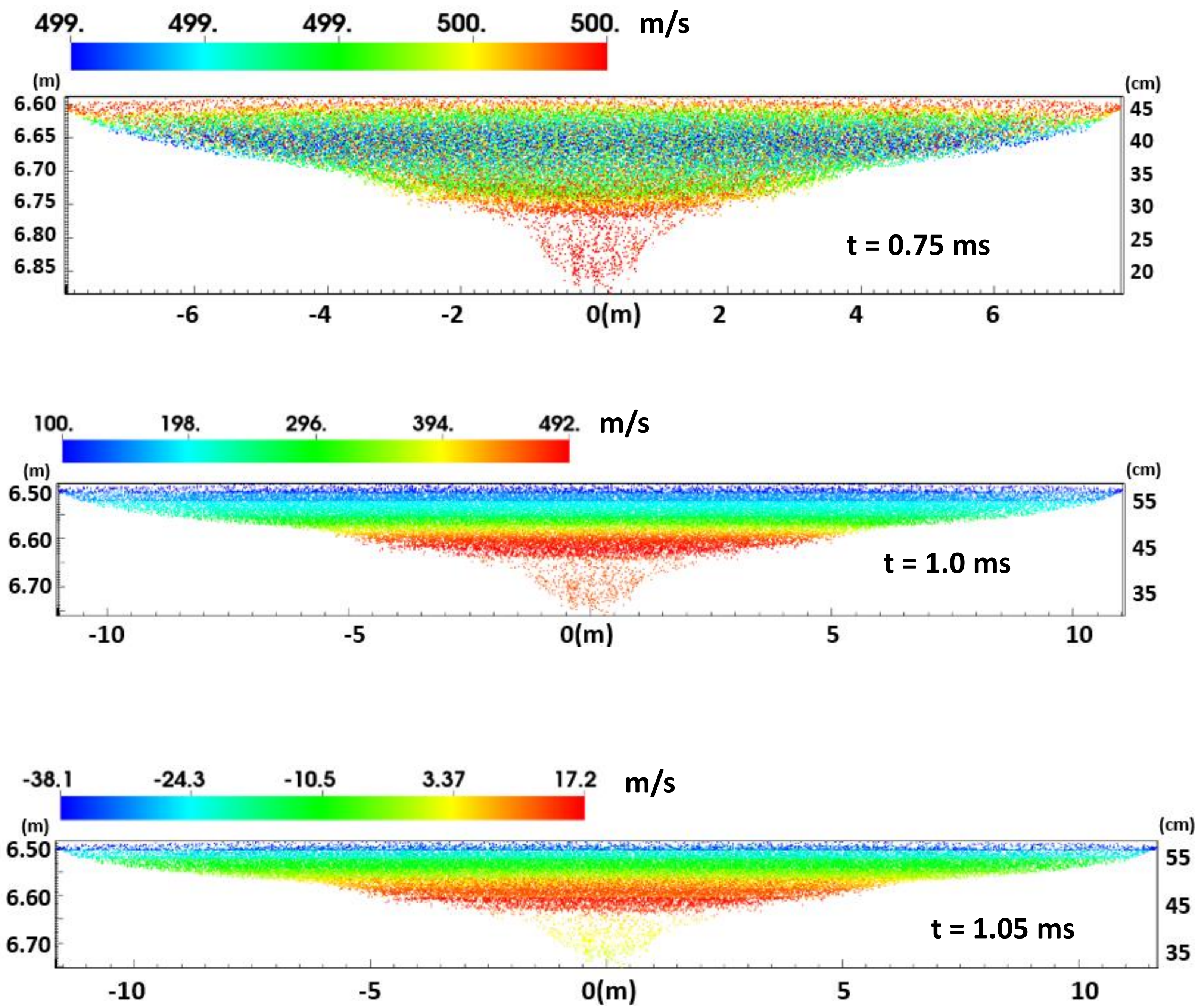
Ratio of the external connection damping and Alfven wave drag terms



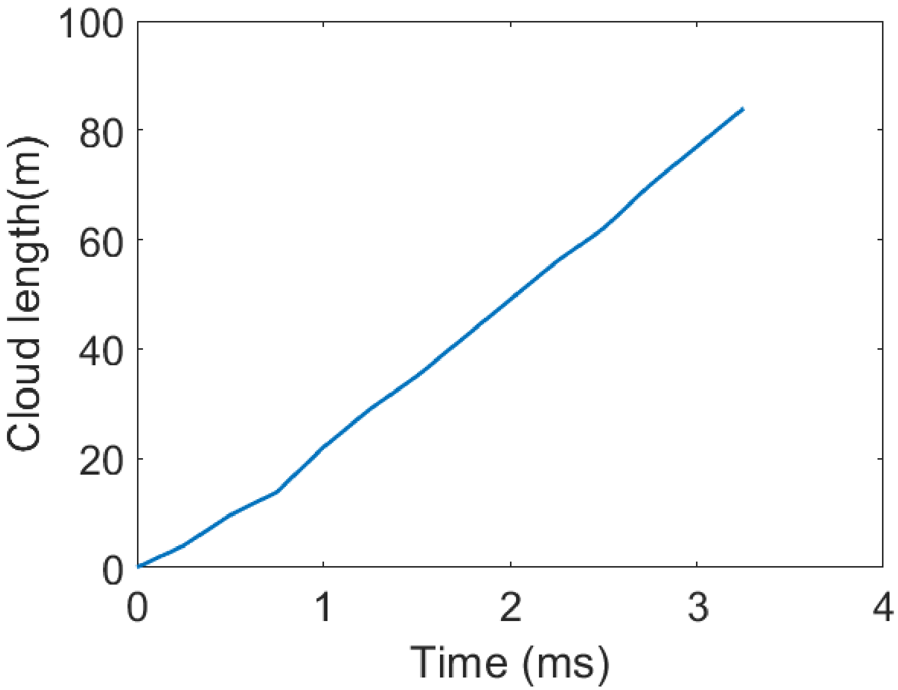


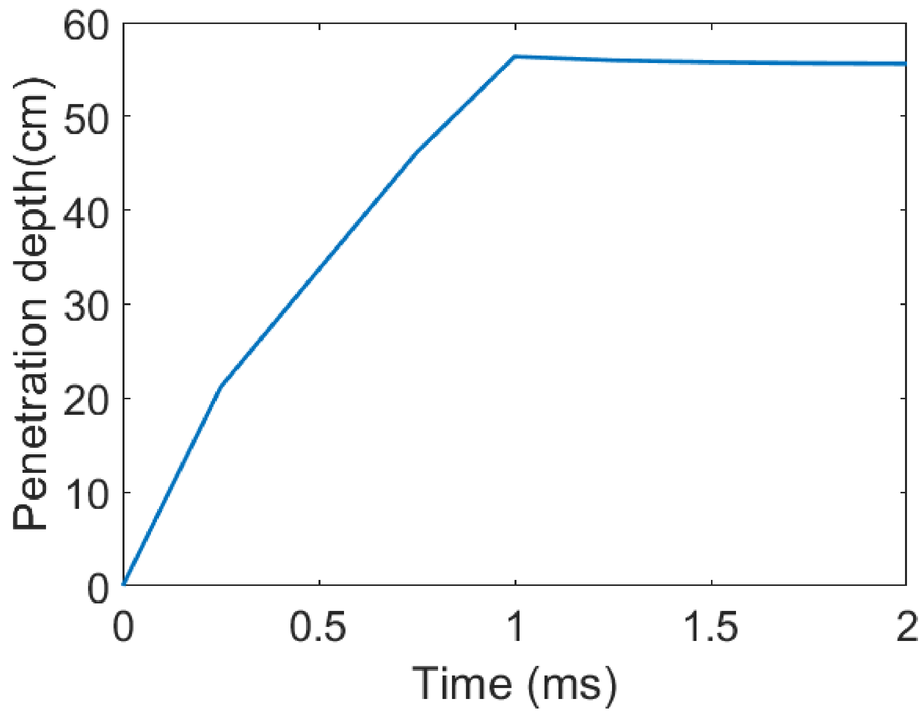
- Top: evolution of connection coefficients for cross-field transport terms
- Bottom: ratio of the external connection (Pegourie) current term to the Alfven wave drag
- After the cloud heats up and ionizes sufficiently that the magnetic field diffusion time becomes longer compared to the transverse advection time, the cross-field drift terms turn-on by the Heaviside function
- The Alfven wave drag is initially large, but it reduces quickly by P_{Alfven} and the Pegourie term takes over
- These two terms and the grad-B drift are responsible for quickly stopping the penetration of the cloud into the RE beam

Drift velocity distribution near maximum penetration depth



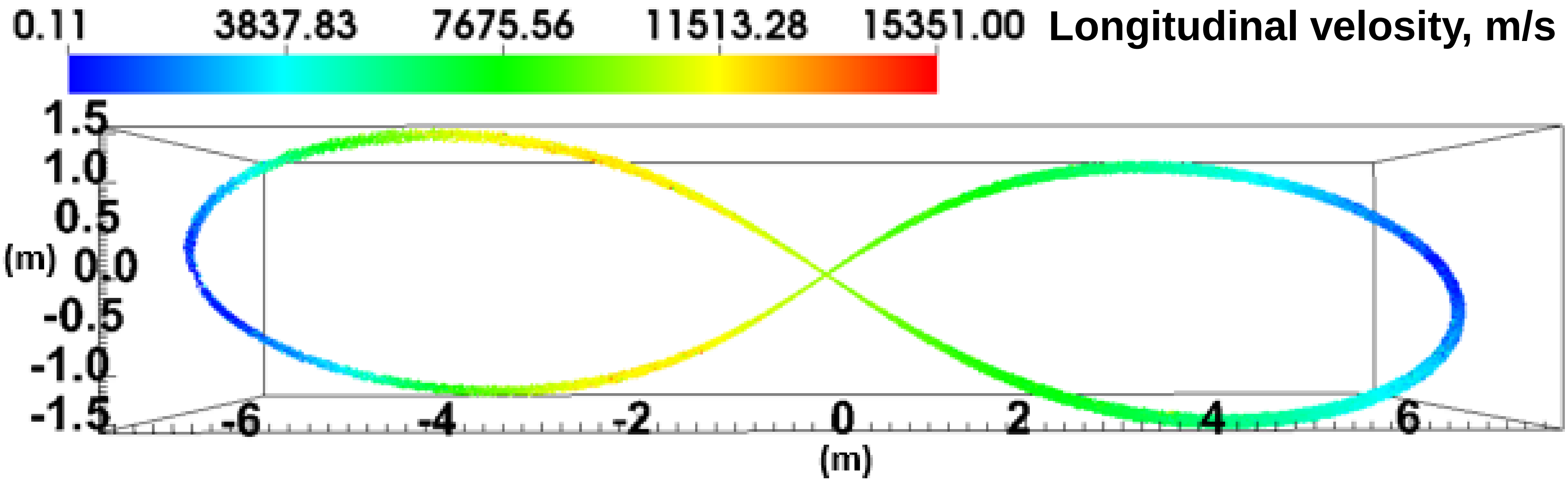
Ablation cloud length and penetration depth into RE beam





- The Alfven wave drag term, the external (Pegourie) connection current term and the grad-B drift are responsible for quickly stopping the penetration of the cloud into the RE beam after the magnetic field diffusion time becomes longer compared to the transverse advection time

Long-term expansion of the ablation cloud at q=2

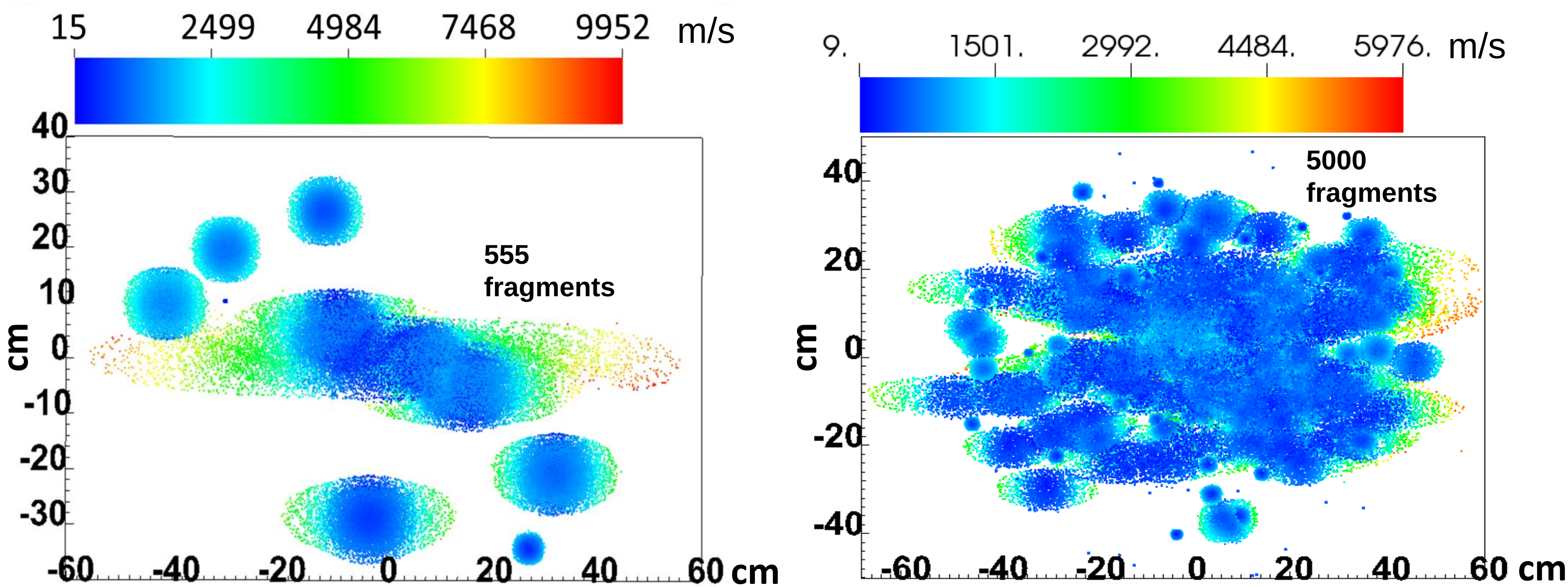


At about 3 ms, the single pellet cloud reconnects longitudinally at q=2.
Distribution of the longitudinal velocity (m/s) is shown.

Single Fragment Simulation: Summary and Conclusions

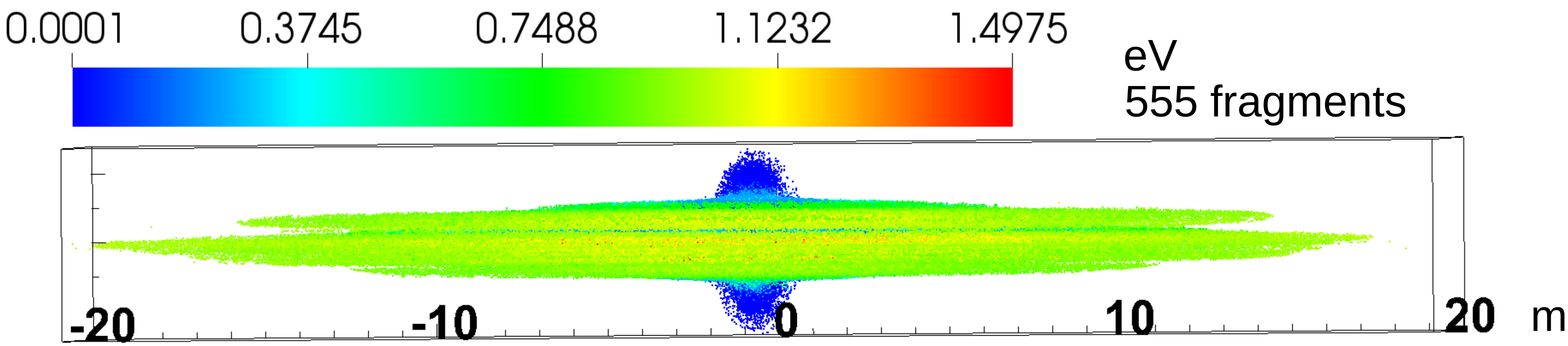
- From 0 to 40μs, the cloud expansion is close to spherical. The radius of the cloud is of the order of 10 cm.
- At about 1 ms, the cloud heats up and ionizes sufficiently and the magnetic field diffusion time becomes longer compared to the transverse advection time. The cross-field drift terms become turned-on by the Heaviside function.
- The Alfven wave drag is initially large, but it reduces quickly by P_{Alfven} and the Pegourie current term takes over. These two terms and the grad-B drift are responsible for rapidly stopping the penetration of the cloud into the RE beam.
- The ablated cloud deepest penetration of 55 cm into RE beam is reached at 1.0 ms. After this, the cloud starts moving slowly in the direction of large R due to the grad-B drift. The motion is slow due to strong damping factors.
- At about 3 ms, the cloud reconnects longitudinally at q=2.
- Within the RE density ramp, the pellet cloud evolution also strongly depends on the impact ionization by energetic electrons. The thermal Saha ionization alone is not sufficient for ionizing the cloud at the edge of the RE beam. Without the impact ionization, the cloud would expand spherically as (almost) neutral gas.

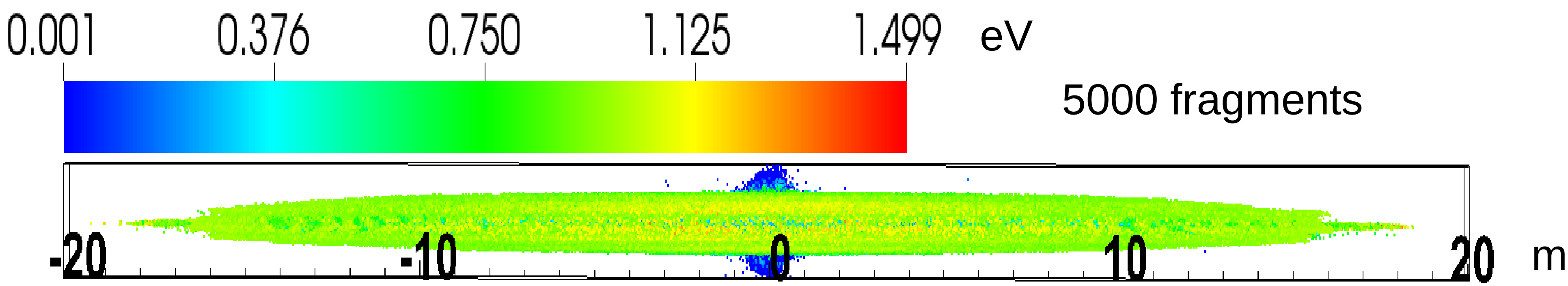
SPI simulation with 555 and 5000 fragments: initial stage of ablation (100μs)



Velocity distribution (m/s) at 100μs in SPI simulation using 555 fragments (left) and 5000 fragments (right). View in the injection direction; direction of the magnetic field is horizontal. Individual cloudlets quickly merge into a single ablation cloud.

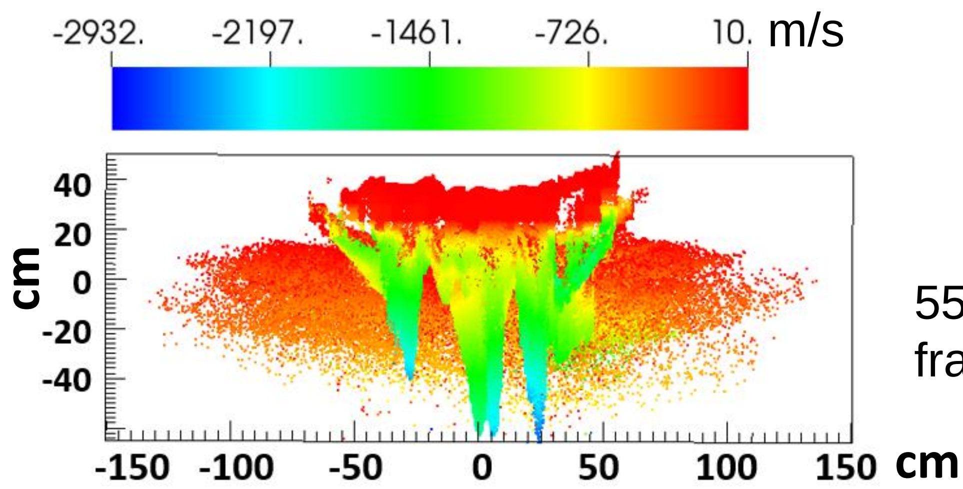
SPI simulation with 555 and 5000 fragments: ablation cloud state near deepest penetration into RA beam (1 ms)



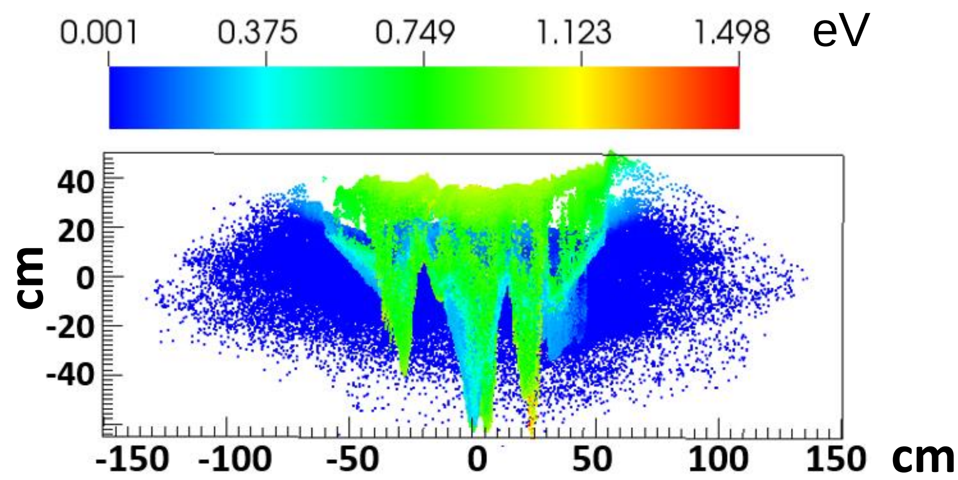


Temperature distribution (eV). View along the injection direction.

SPI simulation with 555 (top) and 5000 (bottom) fragments: ablation cloud state near deepest penetration into RA beam (1 ms)

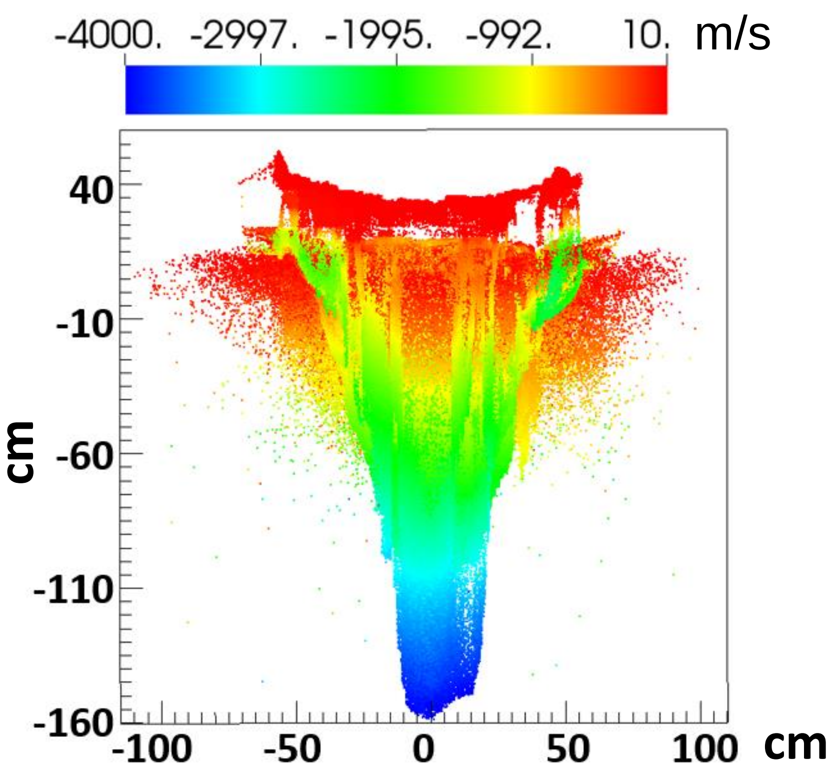


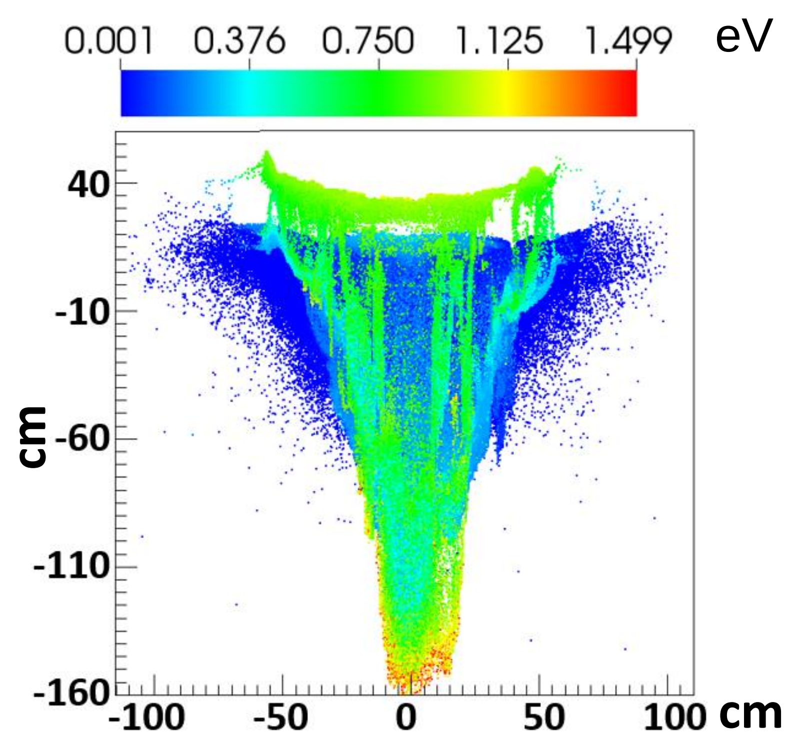
Transverse velocity, m/s



Temperature, eV

555 fragments

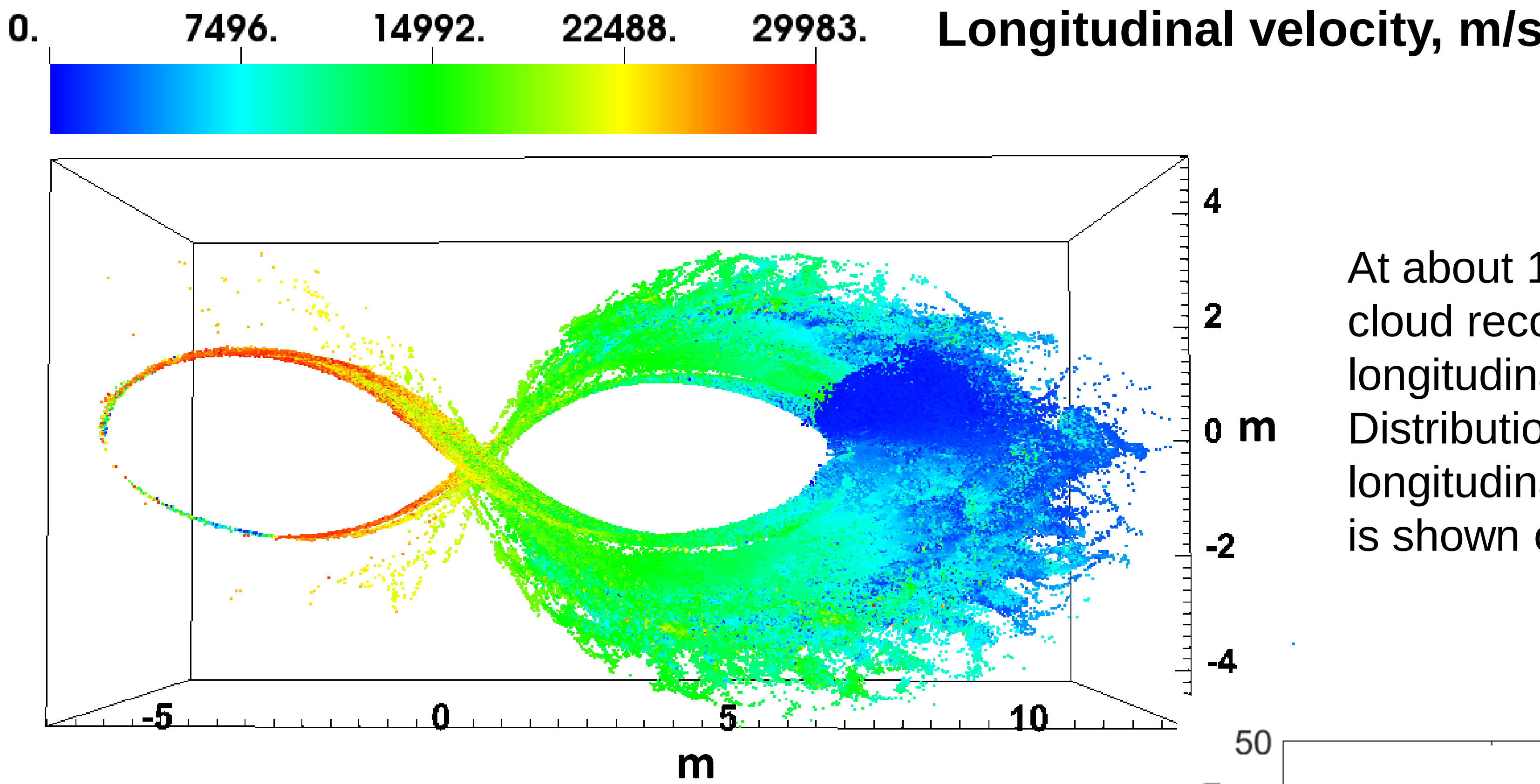




5000 Fragments

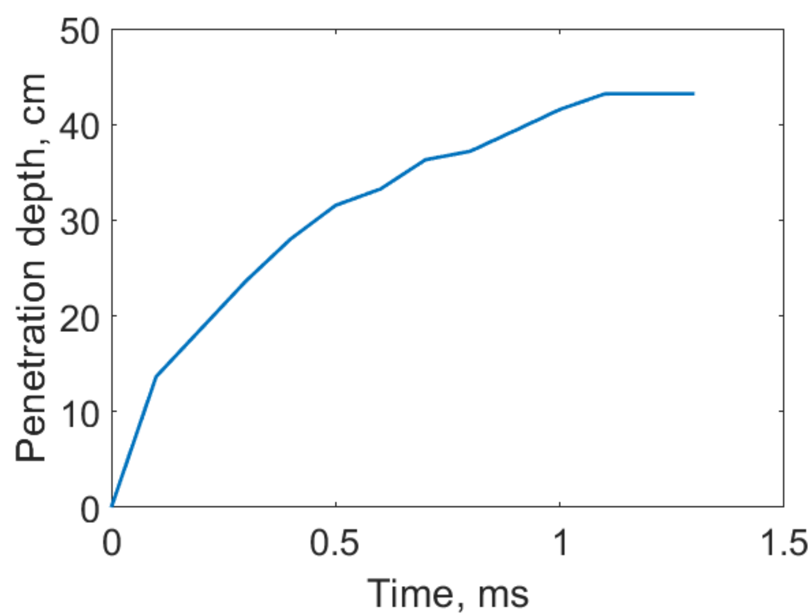
View along magnetic field line.

Long-term expansion of the SPI ablation cloud at q=2



At about 1.7 ms, the SPI cloud reconnects longitudinally at q=2. Distribution of the longitudinal velocity (m/s) is shown on the left.

Penetration depth of the SPI cloud into the runaway beam is shown on the right.



SPI Simulation: Summary and Conclusions

- 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

- We performed simulations of a single hydrogen fragment with different sets of RE parameters to study effects of ionization mechanisms on the cloud evolution
  - The thermal Saha ionization alone is not sufficient for ionizing the cloud at the edge of the RE beam. Ionization by impact is crucial for causing strong MHD effects.
  - Both 3D and 1D simulations showed that the longitudinal heat diffusion provides negligibly small factor in the energy balance.

- Single fragment simulations quantified various terms in the transverse dynamics model. The penetration depth of the ablated cloud into the RE region is about 55 cm, reached at 1.0 ms. At about 3 ms, the cloud reconnects longitudinally at q=2.

- SPI simulations show ablation plasma flows with high grad-B drift. A large neutral cloud is also expelled from the RE region by the pressure gradient. Number of SPI fragments affects the cross-field transport in the ablation cloud.

- The penetration depth of the SPI ablated cloud into the RE region is about 44 cm, reached at 1.1 ms. At about 1.7 ms, the cloud reconnects longitudinally at q=2.