# Afterglow plasma processes in dry-wall IFE chambers

**Sergei Krasheninnikov**

*Presented by*

**Mark S. Tillack**

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# Introduction

- After the fireball expansion stage, the **afterglow phase** starts, characterized by cooling of the plasma-gas mixture and plasma recombination-neutralization processes.

- Usually it is assumed that the plasma is almost completely extinguished between shots (for ~ 0.1 s). However, we show that this may not be the case.

- The presence of rather high density plasma can significantly alter many processes in the chamber. For example:
  - Heat flux to the pellet caused by the recombination of plasma species can significantly exceed the heat flux of kinetic energy of colliding particles.
  - Collective interactions of fast ions from the fireball with residual plasma (*e.g.*, beam-plasma instability) can alter fast ion stopping processes.

# Outline

## 1. First-principles estimates of:

a. Residual particle density,
b. Residual plasma density, and
c. Residual gas/plasma temperature in the chamber

## 2. Impact of residual plasma on:

a. Heat flux to the target
b. Stopping of energetic ions
c. Fireball expansion
d. Thermal electron emission and heat flux to the wall

# 1a. Particle density in the chamber

- The flux of particles into a pump, $\Gamma_{pump}$ must equilibrate with the pellet particle source, $\Gamma_{pellets}$:

$$\Gamma_{pump} \equiv \frac{nV_{th}}{4} S_{pump} \xi_{pump} = \Gamma_{pellets} \equiv f\, N_1$$

where:

$V_{th}$ is the thermal speed (1–3 km/s);

$S_{pump}$ is the surface area of the pump ducts (5 $m^2$);

$\xi_{pump}$ is the pumping efficiency (1–50%);

f is the rep. rate of pellet injection (10 Hz);

$N_1$ is the number of particles in one pellet (~$10^{21}$)

- **$n \sim 10^{18}/\xi \sim 10^{18}$-$10^{20}$ $m^{-3}$** *(note, 1 mTorr~$3x10^{19}$ $m^{-3}$ at 0˚C)*
- The mean free path of cold neutrals is $\lambda_n = 1/n\sigma$, where $\sigma \sim 16x10^{-16}$ $cm^2$.

  At $3x10^{19}$ $m^{-3}$, $\lambda_n \sim 30$ cm < $R_{chamber} = 6.5$ m
- This implies: i) short mean free path (fluid) regime of transport and ii) rather weak impact of diffusive effects

# 1b. Residual plasma density

- Plasma density reduction in the afterglow phase can be due to:

  i) volumetric recombination processes (*e.g.*, 3-body recombination)

  ii) plasma neutralization at the wall of the chamber

## *i) Three-body recombination*

- Three-body recombination is inefficient for plasma densities < 1–10x$10^{18}$ $m^{-3}$, even at low temperature ~0.1 eV

**Characteristic plasma recombination time, $\tau_{rec}$**

| T / $n_{pl}$ | $10^{18}$ $m^{-3}$ | $10^{19}$ $m^{-3}$ | $10^{20}$ $m^{-3}$ |
|---|---|---|---|
| 0.2 eV | ~ 0.1 s | ~ 3x$10^{-3}$ s | ~ $10^{-4}$ s |
| 0.6 eV | ~ 1 s | ~ 0.1 s | ~ 2x$10^{-3}$ s |
| 1.2 eV | ~ 3 s | ~ 0.4 s | ~ $10^{-2}$ s |

- Notice that neutral gas opacity effects, which are not taken into account here, can significantly increase $\tau_{rec}$

# 1b. Residual plasma density

## *ii) Neutralization at the Wall*

- The rate of plasma neutralization on the chamber wall is determined by plasma transport to the wall.
- For the case of diffusive plasma transport to the wall for residual neutral gas density ~$10^{20}$ $m^{-3}$, we have:

$$\tau_{diff} \sim \frac{R^2}{D_{plasma}} \sim 3\frac{R^2}{\lambda_{iN} V_{th}} \sim 0.1 \;\; s \sim f^{-1}$$

- Thus we see that counting both volumetric plasma recombination and diffusive plasma loss to the wall it is difficult to decrease the residual plasma density below $10^{18}$~$10^{19}$ $m^{-3}$.
- It is difficult to estimate the impact of convective effects, however, one can expect that that low scale modes of convective motion of gas/plasma mixture are rather quickly damped by viscosity effects leaving only convective cells with the scale ~ R.
- In that case, the estimates above apply to plasma within these convective cells.

# 1c. Residual gas/plasma temperature

- There are three main mechanism of plasma/gas mixture cooling: i) radiation, ii) conduction, and iii) convection

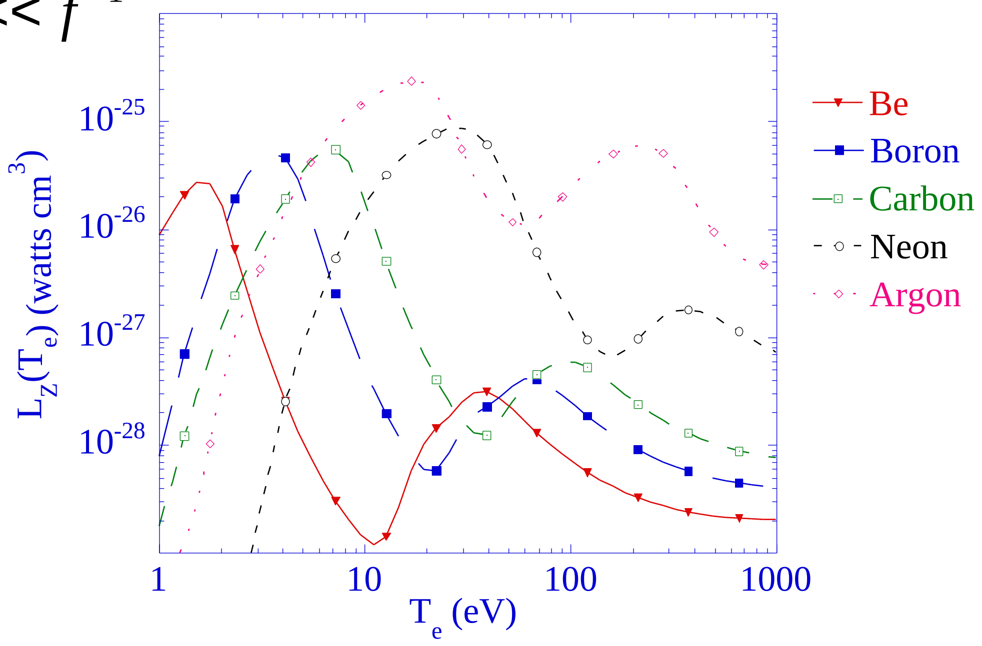
## *i) Radiation*

- During the initial stages of the afterglow phase (T > few eV) line radiation is very effective ($L_{rad}(t) \sim 10^{-25}$ W-cm$^3$) and plasma cooling is characterized by the time scale:

$$\tau_{rad}(T \tilde{\geq} \text{ few eV}) \sim \frac{T}{L(T)n_{pl}} \sim 10^{-3}\ s << f^{-1}$$

- However, for temperatures < 1 eV, line radiation loss is negligibly small:

$\tau_{rad}(T < 1 \text{ eV}) >> f^{-1}$



# 1c. Residual gas/plasma temperature

## *ii) Conduction*

- Electron heat conduction to the walls combined with peripheral electron cooling (*e.g.*, electron-neutral elastic collisions) results in the following time scale of the temperature reduction at **T~1 eV**:

$$\tau_{e-cond}(T\sim 1eV)\sim \frac{n}{n_{pl}}\frac{R^2}{\lambda_e V_{the}}\sim(1-10)\times 10^{-3}s$$

- **At T~0.1 eV we find $\tau_{e\text{-}cond}$(0.1 eV) ~ 0.3–3 s > $f^{-1}$**

- The time scale of the temperature reduction due to heavy particle (ions and neutrals) heat conduction, $\tau_{iN\text{-}cond}$, is comparable to the diffusion time. For a residual neutral gas density ~$10^{20}$ m$^{-3}$, we find:

$$\tau_{iN-cond}\sim 3\frac{R^2}{\lambda_{i,N}V_{th}}\sim 0.1\ s\sim f^{-1}$$

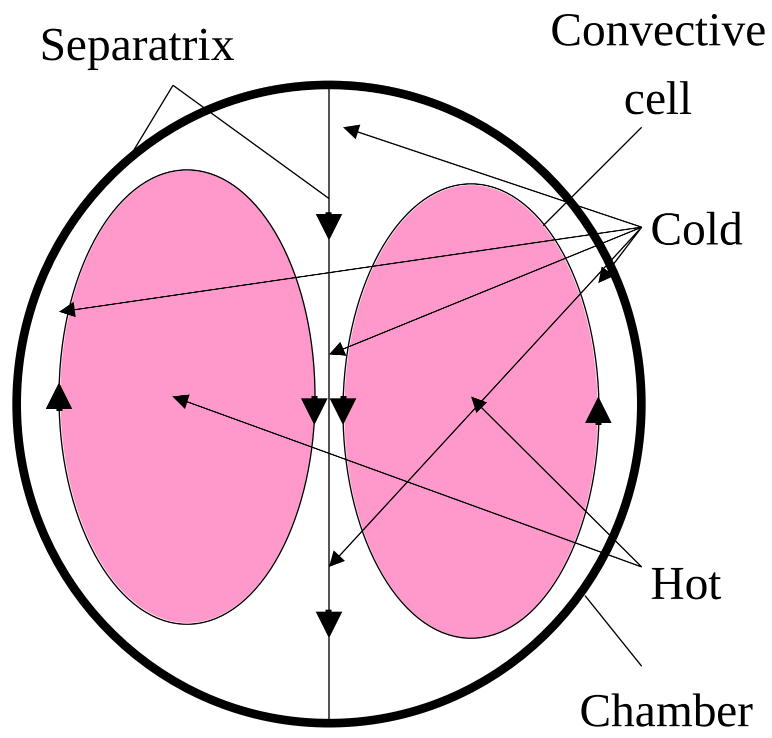
# 1c. Residual gas/plasma temperature

## *iii) Convection*

- One can expect that that short scale-length modes of convective motion of gas/plasma mixture will be quickly damped by viscosity effects leaving only convective cells with the scale ~ R

- Conduction will determine the temperature of the plasma/gas mixture contained within these large convective cells

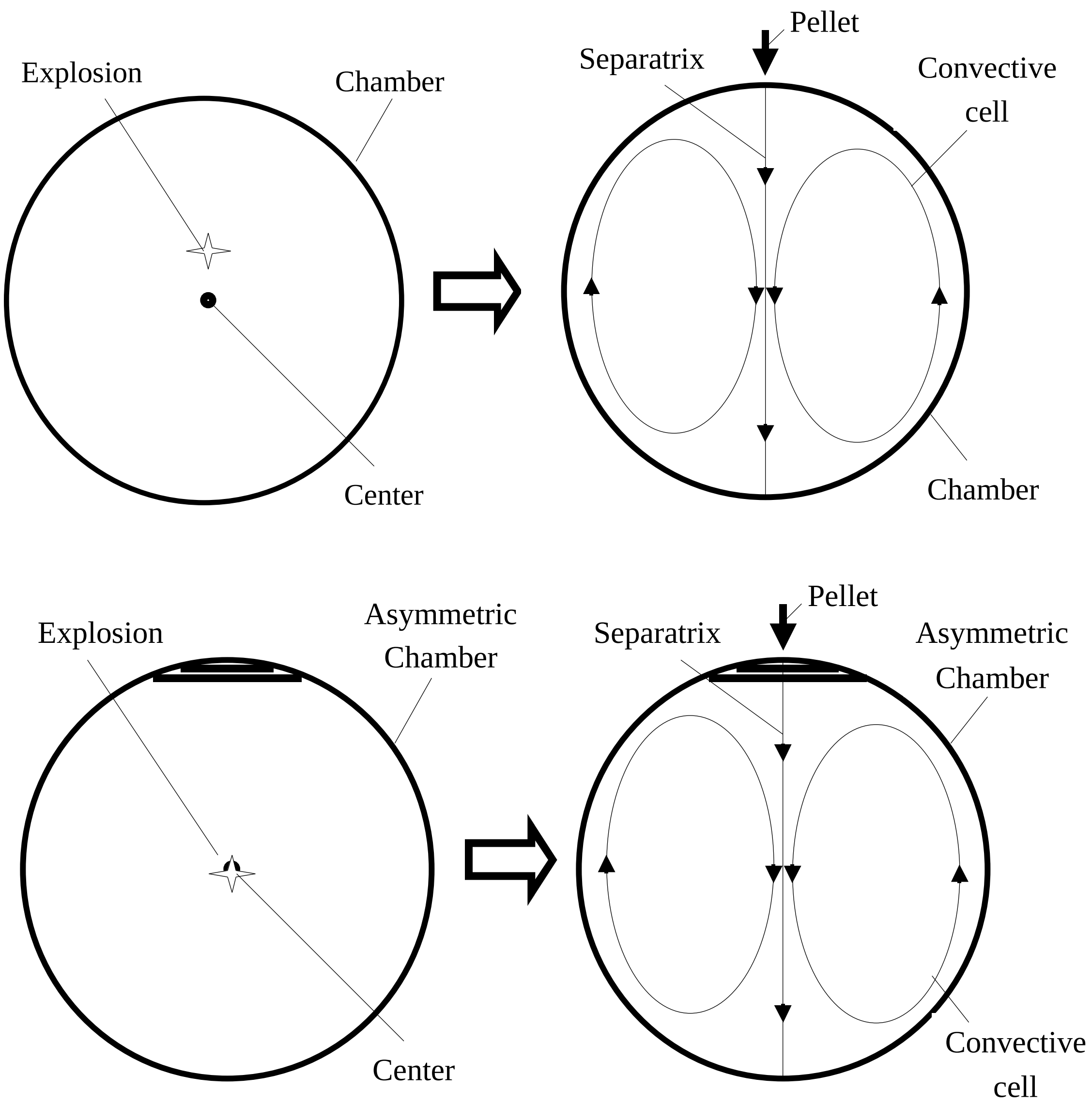
- An interesting and **important** feature of large convective cells is a low temperature of gas/plasma mixture and low plasma density around the separatrix of the flow



# 1c. Residual gas/plasma temperature

## *iii) Convection*

- Large convective cells can be deliberately generated in the chamber and then used to effectively cool the gas and recombine plasma on the pathway of the pellet
- It can be done easily by shifting the pellet explosion from the center of the chamber, or by a slight asymmetry of the chamber



# 2a. Heat flux to the target

***Heating by recombination can be much larger than heating by particle kinetic energy***

- Heat flux to the pellet associated with kinetic energy of incident particles of gas/plasma mixture:

$$q_{ke\text{-}pellet} = (1-R_E)\,\gamma\, j_{in} T_g$$

$R_E$ = reflection coefficient

$\gamma$ = energy transmission coefficient

$j_{in}$ = incident particle flux

$T_g$ = temperature of plasma/gas mixture

- Potential energy released at the surface due to surface recombination of atomic particles into the molecules and plasma surface neutralization :

$$q_{pot\text{-}pellet} = \xi_*\, j_{*in} E_{*pot}$$

$\xi_*$ = probability of process to occur

$j_{*in}$ = corresponding particle flux

$E_{*pot}$ = potential energy corresponding with the process, 4~10 eV

# 2a. Heat flux to the target

- Notice that $E_{*pot} >> T_g$. Therefore, even relatively small content of corresponding atomic particles and plasma can significantly alter the heating of the pellet

- *E.g.*, taking into account that the probability of plasma surface neutralization is close to unity and $(1-R_E)\gamma \sim 1$ for $T_g \sim 0.1$ eV, we find:

$$\frac{q_{pellet}^{neutr}}{q_{pellet}^{kin}} \sim \frac{j_{in}^{pl}}{j_{in}} \frac{I}{T_g} \sim \frac{n_{pl}}{n} \frac{I}{T_g} \sim 100 \frac{n_{pl}}{n}$$

  where I~10 eV is the ionization potential

- For $n_{pl} \sim 10^{19}$ m$^{-3}$ and pellet radius ~ 0.3 cm total recombination heat flux to the pellet is ~16 W (*cf.* <1 W/cm$^2$ for radiation+convection)

- Notice that for a rather high probability of surface recombination of atoms into the molecules this channel can be even more important since we can anticipate dissociation degree of molecules in gas to be close to 1

# 2b. Impact of residual plasma on ion stopping

- For reasonable chamber gas density the impact of binary collisions on stopping of energetic (~ 1 MeV) ions is small
(*e.g.*, for H on Xe at 10 mTorr, dE/dx=87 MeV-cm$^2$/g = 0.05 MeV/m)
- However, collective effects of the interactions of the beam of energetic ions with residual plasma can significantly alter the population of energetic ions
- Total number of fast ions per pellet, $n_{i\text{-fast}} \sim 10^{20}$ m$^{-3}$, results in average ion beam density $n_{i\text{-beam}} \sim 10^{16}$ m$^{-3}$
- During pellet explosion the electron temperature of residual plasma can be quickly heated up by electron heat conduction, so that the electron temperature of residual plasma exceeds the ion temperature.
- As a result, an ion beam instability can develop, which is characterized by the growth rate:

$$\gamma_{i-beam} \sim \omega_{pi} \left( n_{i-beam} / n_{pl} \right)^{1/3}$$

# 2b. Impact of residual plasma on ion stopping

- For $n_{i\text{-beam}} \sim 10^{16}\ m^{-3}$ and, $n_{pl} \sim 10^{18}\ m^{-3}$, we find $\gamma_{i\text{-beam}} \sim 10^{8}\ s^{-1}$
- Assuming that the frequency of effective collisions of the beam with residual plasma is of the order of $\gamma_{i\text{-beam}}$, we find a crude estimate of stopping distance of fast ions caused by collective effects, $L_{i\text{-beam}}$:

$$L_{i-beam} \sim \frac{V_{i-beam}}{\gamma_{i-beam}} \sim 10\ cm << R$$

- A more accurate assessment of the impact of collective effects on fast ion stopping requires both:
  - – a more accurate description of the evolution of residual plasma parameters
  - – a more detailed evaluation of collective interactions of fast components (both electron and ion) with the background gas/plasma

# 2c. Residual gas/plasma interactions with the fireball

- Often it is assumed that both expansion of the fireball and fireball- residual gas/plasma interactions can be described in a fluid approximation ($\lambda/L_{fb}$<<1). This may not be the case.  Comparing the Coulomb mean free path $\lambda_p$ with the fireball characteristic length:

$$\frac{\lambda_p}{L_{fb}} \quad \frac{T_{fb}^2}{n_{fb}L_{fb}} \quad \frac{4\pi R^2 T_{fb}^2}{N_1}$$

where $N_1 = 4\pi R^2 L_{fb} n_{fb}$

- For R~10 m, $N_1$~$10^{21}$ $m^{-3}$, T~1 keV, we find $\lambda_{mfp}/L_{fb}$~$10^4$ >>1

- As a result, only very beginning ($R_{fb}$<~10 cm) of the fireball expansion will go in a fluid regime

- Further expansion as well as the interactions with residual gas/plasma will occur in collisionless regimes where the impact of plasma beam/stream instabilities can play an absolutely crucial role

# 2d. Thermal electron emission and heat flux to the wall

- Ambipolarity of plasma flow to the wall results in a reduction of the large electron free streaming heat flux, $q_{e\text{-}fs} \sim n_{pl} T (T/m)^{1/2}$, down to the plasma free streaming heat flux, $q_{p\text{-}fs} \sim n_{pl} T (T/M)^{1/2} << q_{e\text{-}fs}$, due to sheath effects.

- However, at high wall surface temperature, , which happens just after the explosion, thermal electron emission from the wall can be an important ingredient in power loading of the wall.

- In this case, “cold” thermal electrons replace hot fireball electrons.

- The impact of thermal electrons becomes important when the flux of thermal electrons, $j_{e\text{-}th}$, is comparable or higher then the plasma flux, $j_p \sim n_{pl} (T/M)^{1/2}$

# 2d. Thermal electron emission and heat flux to the wall

- Using Richardson's expression:

$$j_{e-th} = \frac{mT^2}{2\pi^2\hbar^3}\exp\left(-\varphi/T_w\right) \equiv j^*_{e-th}\exp\left(-\varphi/T_w\right)$$

with $j^*_{e\text{-}th} \approx 10^{27}$ cm$^{-2}$s$^{-1}$ and $\phi \approx 4$–$5$ eV

- We find that the impact of thermal electrons becomes important when $T_w > \phi\, ln(j_p/j^*_{e\text{-}th})$
- For $j_p \sim 10^{20}$ cm$^{-2}$s$^{-1}$ we find $T_w > T_{crit} \sim 2000$–$2500$ K
- When $T_w$ exceeds $T_{crit}$, thermal instability can cause hot spots to develop on the surface
- Formation of the hot spots can cause wall overheating and damage

# Conclusions

- The residual density of the gas/plasma mixture can be rather high, $n \sim (1\text{–}10) \times 10^{19}\ m^{-3}$, resulting in a short mean free path (fluid) regime of transport and weak impact of diffusive effects.
- Analysis of plasma recombination and diffusion processes shows that it is difficult to reduce the residual plasma density below $n_{pl} \sim (1\text{–}10) \times 10^{18}\ m^{-3}$.
- While radiation is very effective in gas/plasma energy dissipation for T~ a few eV, it does not work for sub-eV temperatures. Heat conduction mechanisms are not fast enough either. Therefore, it is difficult to expect that the averaged temperature of the gas/plasma mixture can be reduced to ~ 0.1 eV between the shots.
- However, the temperature of the gas/plasma mixture near the separatrix of large convective cells can be reduced to ~ 0.1 eV or less. Such a cell can be deliberately generated in the chamber. Notice that convective cells can help protect the pellet.

# Conclusions

- Potential energy released on the pellet due to collisions and recombination of atomic and plasma species can significantly exceed the heat flux to the pellet due to just kinetic energy of colliding particles
- Crude estimate of stopping distance of fast ions caused by collective effects shows that it is feasible to expect that these effects can result in a drastic reduction the population of energetic ions
- Interactions of the fireball with residual gas/plasma will predominantly occur in a collisionless regime where plasma-beam/stream instabilities can be very important
- Thermal electron emission from the wall can be important for power loading and the formation of hot spots