

IFE Chamber Ionization and Effect on Target Injection

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Outline

I. Introduction

II. On residual particle density in the chamber

III. On residual plasma/gas temperature

IV. On residual plasma density

V. On the heat flux to the target

VI. Numerical modeling

VII. Conclusions

Introduction

- After a short (few μ s) phase of the fireball expansion in the IFE chamber, much longer *the afterglow phase* starts which goes for ~ 0.1 s before another target is injected and exploded in the chamber
- The main processes in afterglow phase:
 - i) cooling of the plasma-gas mixture,
 - ii) plasma recombination-neutralization processes, and
 - iii) slowing of plasma/gas flows

- The afterglow phase sets the chamber conditions for next target injection
- Since modern direct drive targets do not produce much X-ray radiation the need for the gas (Xenon) filling to protect the wall surface from the overheating is gone and we will assume that the only gas in the chamber is residual one
- Here we touch some of rather complex processes of the afterglow phase

On residual particle density in the chamber

- Due to finite pumping speed, the residual particle density, n_{res} , (gas and plasma) in the IFE chamber is relatively high
- Target injection = particle flux into a pump (trapping in the wall is small)

$$(n_{\text{res}} V_{\text{th}} / 4) S_{\text{pump}} \eta_{\text{pump}} = f N_1 \quad \Rightarrow \quad n_{\text{res}} \sim (1 \div 10) \times 10^{19} \text{ m}^{-3}$$

$V_{\text{th}} \sim (1 \div 3) \times 10^3 \text{ m/s}$ is the thermal speed of the neutrals

$S_{\text{pump}} \sim 100 \text{ m}^2$ is the surface area of pump ducts

$\eta_{\text{pump}} \sim (1 \div 3) \times 10^{-2}$ is the pumping efficiency

$f \sim 10 \text{ Hz}$ is the repetition rate of target injection

$N_1 \sim 10^{21}$ is the number of particles in one target

- As a result, the mean free path of plasma/neutral particle, λ_n , is small

$$\lambda_n \sim 1 \text{ } \mu\text{m} \ll R_{\text{ch}} \sim 10 \text{ m}$$

where R_{ch} is the chamber radius.

- It implies:
 - i) short mean free path (fluid) regime of both plasma and neutral gas transport
 - ii) rather weak impact of diffusive effects.
 - iii) strong trapping of line radiation

On residual plasma/gas temperature

- There are three mechanisms of plasma/gas mixture cooling:
 - i) radiation
 - ii) heat conduction
 - iii) convection

i) Radiation

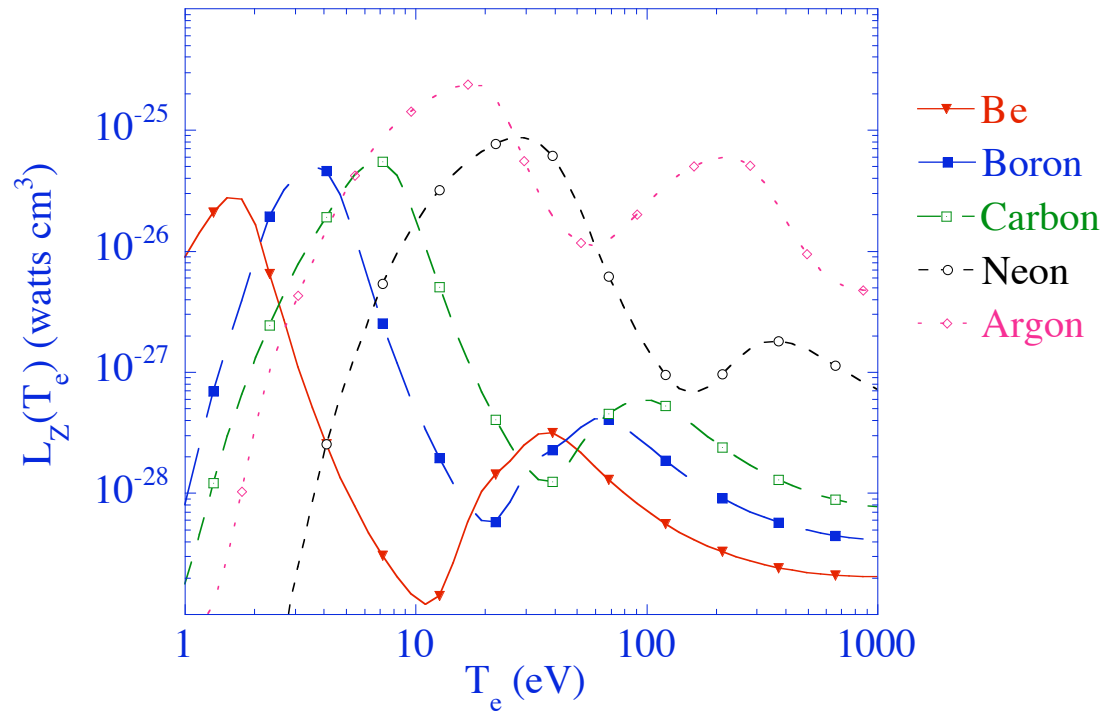
- On initial stages of afterglow phase ($T > \text{eV}$) line radiation can be very effective; even impurity, $\square_{\text{imp}} = n_{\text{imp}} / n_{\text{pl}} \sim 10^{-2}$, plasma cooling is characterized by the time scale

$$\square_{\text{rad}}(T \sim 10 \text{ eV}) \sim T / L(T \sim 10 \text{ eV}) n_{\text{pl}} \square_{\text{imp}} \sim 10^{-4} \text{ s} \ll 1/f \sim 0.1 \text{ s},$$

$$L_{\text{rad}}(T \sim 10 \text{ eV}) \sim 10^{-25} \text{ W} \cdot \text{cm}^3 \text{ is impurity radiation function}$$

- However, for the temperatures below or about 1 eV line radiation loss is negligibly small and

$$\tau_{\text{rad}}(T \lesssim 1 \text{ eV}) \gg 1/f \sim 0.1 \text{ s}$$



ii) Conduction

- Electron heat conduction to the walls combined with peripheral electron cooling (e g. electron-neutral elastic collisions) can result in rather fast temperature reduction at $T \sim 3 \text{ eV}$

$$\tau_{e\text{cond}}(T \sim 3 \text{ eV}) \sim 3(n_{\text{res}} / n_{\text{pl}})(R_{\text{ch}}^2 / \lambda_e^2 V_e) \sim 0.01 \text{ s},$$

λ_e and V_e are the electron mean free path and thermal speed

- However, due to a strong temperature dependence of electron heat conduction, at $T \sim 1 \text{ eV}$ we find

$$\tau_{e\text{cond}}(T \sim 1 \text{ eV}) \sim 0.1 \text{ s} \sim 1/f$$

- Time scale of the temperature reduction due to neutral gas heat conduction, $\tau_{N\text{cond}}$, is comparable to both plasma particle, τ_{diff} , and momentum, τ_{visc} , diffusion time scales

- For residual neutral gas density $\sim 3 \times 10^{19} \text{ m}^{-3}$ we find

$$\tau_{N\text{cond}} \sim \tau_{\text{diff}} \sim \tau_{\text{visc}} \sim 3 \left(R_{\text{ch}}^2 / \kappa^2 n_N V_{\text{th}} \right) \sim 1 \text{ s} \gg 1/f \sim 0.1 \text{ s}$$

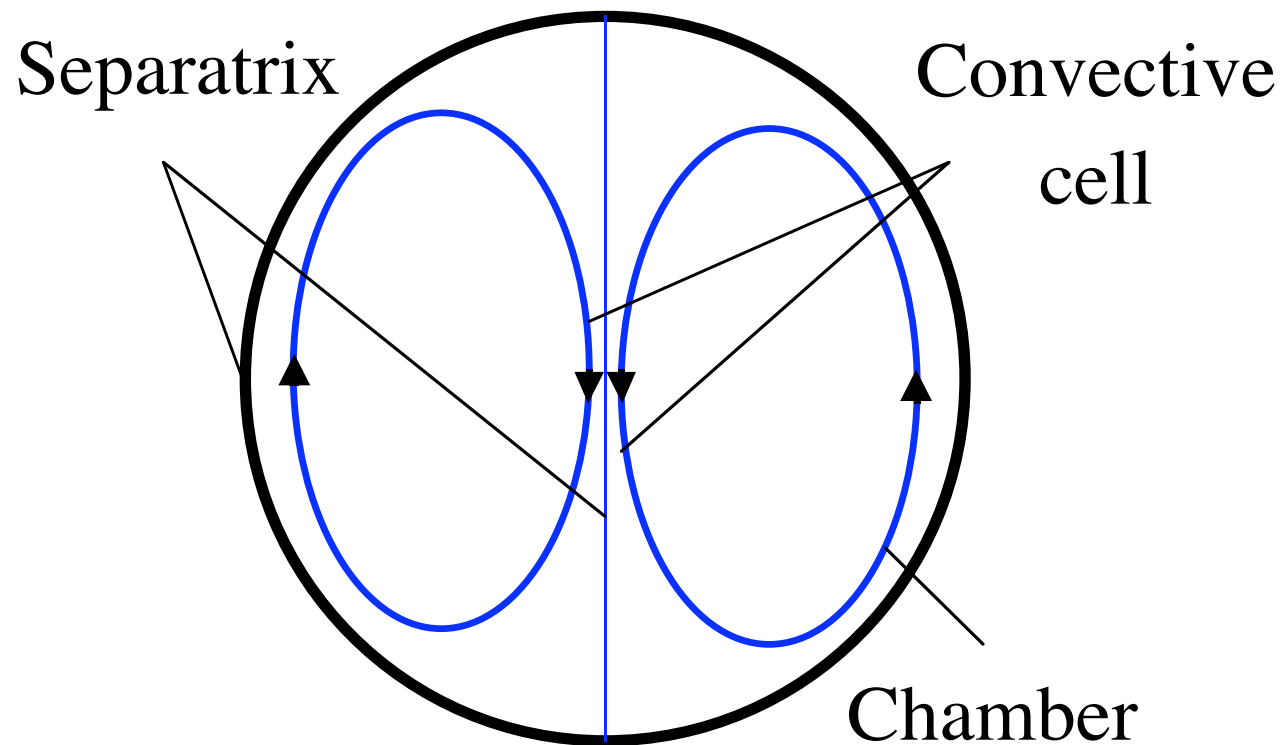
- As we see conduction mechanism alone unlikely results in the reduction of residual gas/plasma temperature to sub-eV level

iii) Convection

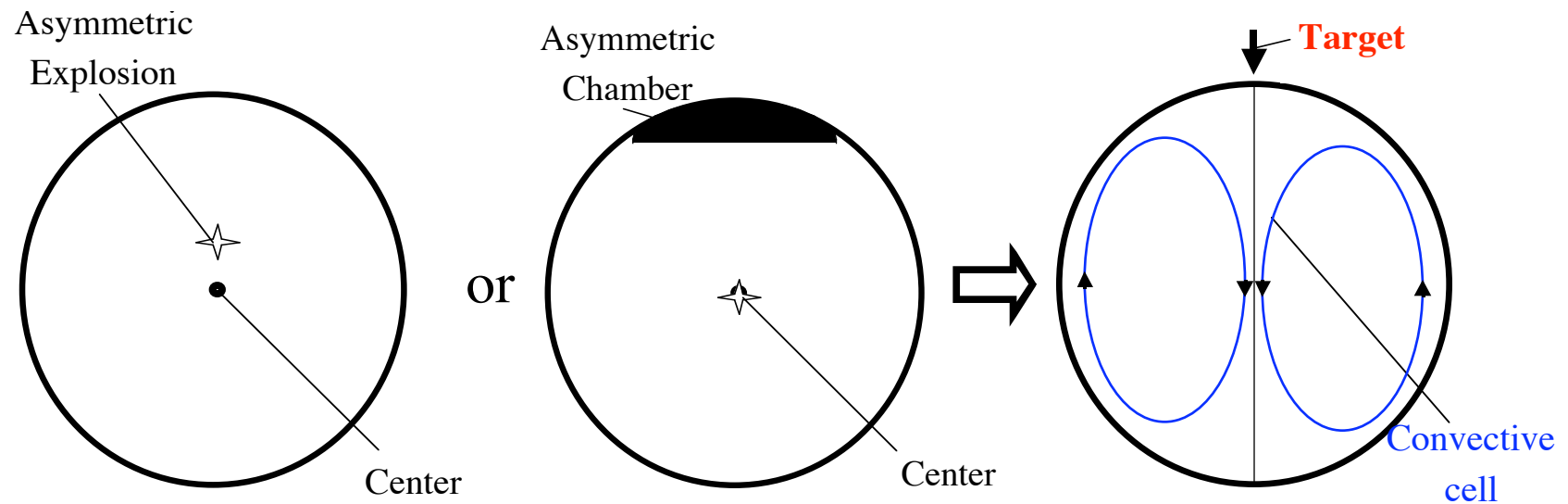
- One can expect that that small scale modes of convective motion of gas/plasma mixture are quickly dumped by viscosity effects leaving only convective cells with the scale $\sim R_{ch}$

$$\tau_{\text{visc}} \sim 3 \left(R_{ch}^2 / \eta^2 n V_{th} \right) \sim 1 \text{ s} \gg 1/f \sim 0.1 \text{ s}$$

- However, 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



- 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 target



On residual plasma density

- Plasma density drop in afterglow phase can be due to:
volumetric recombination and plasma neutralization at the wall
- However, for time scale $\sim 1/f \sim 0.1\text{s}$ recombination becomes inefficient for $n_{\text{pl}} \lesssim (0.1 \div 1) \times 10^{19} \text{ cm}^{-3}$ even at $T \sim 0.1\text{eV}$

$T \setminus n_{\text{pl}}$	10^{18} m^{-3}	10^{19} m^{-3}	10^{20} m^{-3}
0.2 eV	$\tau_{\text{rec}} \sim 0.1 \text{ s}$	$\sim 3 \times 10^{-3} \text{ s}$	$\sim 10^{-4} \text{ s}$
0.6 eV	$\sim 0.8 \text{ s}$	$\sim 5 \times 10^{-2} \text{ s}$	$\sim 2 \times 10^{-3} \text{ s}$
1.2 eV	$\sim 2 \text{ s}$	$\sim 0.15 \text{ s}$	$\sim 10^{-2} \text{ s}$

- Notice that neutral gas opacity effects, which are not taken into account here, can increase τ_{rec} even more
- The rate of plasma neutralization on the chamber wall is determined by the plasma transport to the wall
- For diffusive plasma transport to the wall for residual neutral gas density $n_{\text{res}} \sim 3 \times 10^{19} \text{ m}^{-3}$ we have $\tau_{\text{diff}} \sim 1 \text{ s} \gg 1/f \sim 0.1 \text{ s}$
- Thus, counting only volumetric plasma recombination and diffusive plasma loss to the wall it is difficult to decrease residual plasma density below

$$n_{\text{pl}} \sim 10^{19} \text{ m}^{-3}$$

- It is difficult to estimate the impact of convection effects
- One can expect that that small scale modes of convective motion of gas/plasma mixture are rather quickly damped by viscosity effects leaving only convective cells with the scale $\sim R_{ch}$
- Then, estimates $n_{pl} \sim 10^{19} \text{ m}^{-3}$ can also be applied for the plasma containing inside these large convective cells.
- However, plasma density at the separatrix of the convective cell can be much lower due to cooling effects

On the heat flux to the target

- Cryogenic target is very fragile and can only withstand ~ 1 W of the heat while it travels through the chamber
- Target heats up due to radiation flux and collisions with the particles of gas/plasma mixture
- The heat flux to the target associated with kinetic energy of incident particles of gas/plasma mixture is

$$q_{\text{target}}^{\text{kin}} = (1 - R_E) \alpha j_{\text{in}} T,$$

j_{in} is the flux of incident particles,
 T is the temperature of gas/plasma mixture,
 α is the energy transmission coefficient, and
 R_E is the energy reflection coefficient

- However, potential energy released at the surface due to surface recombination of atomic particles into the molecules and plasma surface neutralization result in significant addition to the heat flux on the target

$$q_{\text{target}}^{\text{pot}} = \sum_i j_{\text{in}}^i E_{\text{pot}}^i,$$

where $E_{\text{pot}}^i \sim 4 - 10 \text{ eV}$ is the potential energy,
 α_i is the probability of the process to occur,
 j_{in}^i is the flux of corresponding particles

- Notice that $E_{\text{pot}} \gg T$, therefore, even relatively small content of corresponding atomic particles and plasma can significantly alter the heating of the target
- For plasma recombination at the target surface we find

$$\frac{q_{\text{target}}^{\text{recomb}}}{q_{\text{target}}^{\text{kin}}} \sim \frac{j_{\text{in}}^{\text{pl}}}{j_{\text{in}}} \frac{I}{T} \sim \frac{n_{\text{pl}}}{n_{\text{res}}} \frac{I}{T} \sim 100 \frac{n_{\text{pl}}}{n_{\text{res}}}$$

- For $n_{\text{pl}} \sim 10^{19} \text{ m}^{-3}$ and the target radius $\sim 0.3 \text{ cm}$ total heat flux to the target associated with the plasma recombination is

$$Q_{\text{target}}^{\text{recomb}} \sim 16 \text{ W} \text{ which significantly exceeds tolerable limit}$$

Numerical modeling

$$n_e + n_n = n_0 = \text{const}$$

$$\frac{\partial n_e}{\partial t} = -\frac{\pi^2 \cdot D}{R^2} \cdot n_e - S_{ion} \cdot n_o \cdot n_e - S_{rec} \cdot n_e^2$$

$$\frac{\partial}{\partial t} \left[\frac{3}{2} T \cdot (n_e + n_o) + I \cdot n_e \right] = \nabla [(K_e + K_n) \cdot \nabla T] - R_{rad} + \left(\frac{\partial n_e}{\partial t} \right)_{wall} \cdot \left(\frac{3}{2} T + I \right)$$

S_{ion} (S_{rec}) is ionization (recombination) rate coefficients

W_{rec} (W_{ion}) is the recombination (ionization) energy losses

K_e and K_n are the electron and neutral heat diffusivities

R_z is impurities radiation loss

- Initial conditions: $T_0=10\text{eV}$, $n_{e0}=n_0$
- Time interval of calculations: 10^{-6} -1s

Conclusions

- Residual density of the gas/plasma mixture in $R_{\text{ch}} \sim 10$ m radius chamber can be rather high, $n_{\text{res}} \sim (1 \div 10) \times 10^{19} \text{ m}^{-3}$, just due to pumping limitation
- It results in a short mean free path (fluid) regime of transport and a weak impact of diffusive effects
- Analysis of the gas/plasma cooling shows that it is difficult to expect that averaged temperature of gas/plasma mixture can be reduced to sub-eV level between the shots

- Due to relatively high temperature of gas/plasma mixture plasma recombination becomes ineffective for residual plasma density below $\sim 10^{19} \text{ m}^{-3}$ and plasma diffusion to the wall is not fast enough either
- As a result, expected residual plasma density is $n_{\text{pl}} \sim 10^{19} \text{ m}^{-3}$
- Presence of rather high density plasma can significantly alter many processes such as metal condensation and heating of the target while it moves through the chamber

- Potential energy released on the target due to surface recombination of plasma can significantly exceed the heat flux due to just kinetic energy
- We notice that both temperature and the plasma density near the separatrix of large convective cells can be significantly reduced which can crucially relax the heat flux to the target injected along such separatrix
- Such convective cell can be deliberately generated in the chamber