*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, O-4.05 (2002)*

IFE Dry Wall Chamber Physics Issues

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Abstract. In the studies of inertial fusion energy (IFE) the physics of the fireball expansion and afterglow stage of plasma/gas evolution in the IFE chamber plays important role for both protection of the chamber first wall and conditions for next target injection which will follow in a time scale ~0.1s. In this report we discuss the results of the analysis of the main physics processes including residual gas/plasma cooling and recombination, the effects of residual plasma on the heat flux to the target, the impact of large convective cells on gas/plasma cooling and recombination processes, and possible effects of collective phenomena on fireball's fast ion and electron dynamics.

Introduction. After a very short (few μs) phase of the fireball expansion, much longer *the afterglow phase* starts which occupies most of the time (~0.1 s) between the shots and is characterized by the cooling of the plasma-gas mixture and the plasma recombination-neutralization processes. Here we just touch some of these very complex issues. Since modern direct drive targets [1] do not produce much X-ray radiation (e. g. [2, 3]) the need for the gas (Xenon) filling is gone and we will assume that the only gas in the chamber is residual one.

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. Equilibrating the particle flux into a pump, $\Gamma_{pump} = (nV_{th}/4)S_{pump}\xi_{pump}$, with particle source due to target injection, $\Gamma_{target} = fN_1$, we find

$$n_{res} \sim (1-10)\times 10^{19}\,\mathrm{m}^{-3}, \qquad (1)$$

we assumed that: $V_{th} \sim (1-3)\times 10^{3}\,\mathrm{m/s}$ is the thermal speed of the neutrals; $S_{pump} \sim 100\,\mathrm{m}^2$ is the surface area of pump ducts; $\xi_{pump} \sim (1-3)\times 10^{-2}$ is the pumping efficiency; $f \sim 10\,\mathrm{Hz}$ 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

$$\lambda_n \sim 1-10\,\mathrm{cm} << R_{ch} \sim 10\,\mathrm{m}, \qquad (2)$$

where R_{ch} is the chamber radius. It implies: i) short mean free path (fluid) regime of both plasma and neutral gas transport and ii) rather weak impact of diffusive effects.

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

i) Radiation. On initial stages of afterglow phase (T > eV) line radiation can be very effective and even with one percent of impurity, $\xi_{imp} = n_{imp}/n_{pl}$, plasma cooling is characterized by the time scale

$$\tau_{rad}(T\sim 10\text{ eV}) \sim T/L(T\sim 10\text{ eV})n_{pl}\xi_{imp} \sim 10^{-4}\text{ s} << 1/f, \qquad (3)$$

where $L_{rad}(T)$ is the impurity radiation function, $L_{rad}(T\sim 10\,\mathrm{eV}) \sim 10^{-25}\,\mathrm{W\cdot cm^3}$ [4]. However, for the temperatures below or about 1 eV line radiation loss is negligibly small [4] and $\tau_{rad}(T \lesssim 1\text{ eV}) >> 1/f$.

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 $T \sim 3\ \mathrm{eV}$,

$$\tau_{e-cond}(T \sim 3\ \mathrm{eV}) \sim 3(n_{res}/n_{pl})(\pi^2 R_{ch}^2/\lambda_e V_e) \sim 0.1\,\mathrm{s}, \qquad (4)$$

where λ_e and V_e are the electron mean free path and thermal speed respectively. However, due to a strong temperature dependence of electron heat conduction, at $T \sim 1\ \mathrm{eV}$ we find $\tau_{e-cond}(T \sim 1\ \mathrm{eV}) \sim 1\,\mathrm{s} > 1/f$. Time scale of the temperature reduction due to neutral gas heat conduction, τ_{N-cond}, is comparable to both plasma, τ_{diff}, and momentum, τ_{visc}, diffusion time scales. For residual neutral gas density $\sim 3\times 10^{19}\ \mathrm{m}^{-3}$ we find

$$\tau_{N-cond} \sim \tau_{diff} \sim \tau_{visc} \sim 3\left(\pi^2 R_{ch}^2/\lambda_N V_{th}\right) \sim 1\,\mathrm{s} >> 1/f. \qquad (5)$$

As we see conduction mechanism alone cannot result 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 $\sim R_{ch}$ (for the estimate of τ_{visc} see Eq. (5)). Then, Eq. (5) can also be applied for the temperature of the plasma/gas mixture containing within these large convective cells. 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 (see Fig. 1). 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. It easy can be done by shifting the target explosion from the center of the chamber, or by a slight asymmetry of the chamber design, Fig. 2.

On residual plasma density. Plasma density drop in afterglow phase can be due to: volumetric recombination processes (e. g. three body recombination) plasma neutralization at the wall of the chamber. However, for the time scale $\sim 1/f \sim 0.1\,\mathrm{s}$, three body recombination becomes inefficient for the plasma densities $n_{pl} \lesssim (0.1-1)\times 10^{19}\,\mathrm{cm}^{-3}$ even at a very low temperature $\sim 0.1\,\mathrm{eV}$ (see characteristic recombination time, τ_{rec}, in Table 1). 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 the case of diffusive plasma transport to the wall for residual neutral gas density $n_{res} \sim 3\times 10^{19}\,\mathrm{m}^{-3}$ we have estimate (5) $\tau_{diff} \sim 1\,\mathrm{s} >> 1/f$. Thus we see that counting both volumetric plasma recombination and diffusive plasma loss to the wall it is difficult to decrease residual plasma density below

$$n_{pl} \sim 10^{19}\,\mathrm{m}^{-3}. \qquad (6)$$

It is difficult to estimate the impact of convection effects. However, one can expect that that low scale modes of convective motion of gas/plasma mixture are rather quickly dumped by viscosity effects leaving only convective cells with the scale $\sim R_{ch}$. Then, estimates (5) and can also be applied for the plasma containing inside these large convective cells.

On heat flux to the target. 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 $q_{target}^{kin} = (1-R_E)\gamma\, j_{in} T$, where j_{in} is the flux of incident particles, T is the temperature of gas/plasma mixture, γ 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 $q^{pot}_{target} = \xi_* j^*_{in} E^*_{pot}$, where $E^*_{pot} \sim 4-10$ eV is the potential energy associated with the process, ξ_* is the probability of the process to occur, j^*_{in} is the flux of corresponding particles. Notice that $E^*_{pot} >> T$, therefore, even relatively small content of corresponding atomic particles and plasma can significantly alter the heating of the target. For example, taking into account that the probability of plasma recombination at the target surface is close to unity and $(1-R_E)\gamma \sim 1$ we find

$$q^{recomb}_{target} / q^{kin}_{target} \sim (j^{pl}_{in} / j_{in})(I/T) \sim (n_{pl}/n_N)(I/T) \sim 100(n_{pl}/n), \qquad (7)$$

where we assume $T \sim 0.1$ eV, $I \sim 10$ eV is the ionization potential, and n_N is the neutral gas density. For $n_{pl} \sim 10^{19}\,\mathrm{m}^{-3}$ and the target radius ~0.3 cm total heat flux to the target associated with the plasma recombination is $Q^{recomb}_{target} \sim 16\,\mathrm{W}$ which significantly exceeds tolerable limit [5]. We notice that for rather high probability of surface recombination of atoms into the molecules this channel can also be important since we can anticipate dissociation degree of molecules in gas to be close to 1.

On residual gas/plasma interactions with the fireball. We discuss the interactions with residual gas/plasma of the bireball's i) radiation,ii) electrons and fast ions, and iii) blast itself.

i) Radiation. Residual gas/plasma (mostly deuterium and tritium) with the density $n_{res} \sim (1-10)\times 10^{19}\,\mathrm{m}^{-3}$, is transparent for the fireball radiation. Probability, ξ_{ion}, for residual neutrals to be ionized by the fireball radiation with characteristic photon energy, E_{ph}, can be estimated as

$$\xi_{ion} \sim \xi_{rad}\left(a_B^2 / 4\pi R_{ch}^2\right)(E_{exp1}/I)(I/E_{ph})^{9/2}, \qquad (6)$$

where E_{exp1} is the energy of explosion in the plasma; ξ_{rad} is the portion of the explosion energy going into radiation, I is the ionization potential ($I < E_{exp1}$), and a_B is the Bohr radius. For $E_{exp1} \sim 60$ MJ, $I/E_{ph} \sim 0.1$, and $R_{ch} \sim 10$ m, we find $\xi_{ion} << 1$. As a result, radiation does not alter much plasma and neutral gas densities in entire chamber, even though close to the epicenter of the explosion the radiation impact on residual gas/plasma constituency is large.

ii) Electrons and fast ions. The energy exchange between fireball and residual electrons due to heat conduction can be an important issue. Since residual gas/plasma is almost transparent for hot ($\tilde{>}$ keV) electrons therefore this transport can be fast. In almost collisionless limit electron heat transport is limited only by backflow of cold residual electrons which may be accompanied by plasma turbulence (e. g. acoustic instability [6]). Moreover, the interactions of fast ($\sim$ MeV) ions with electron (or even self-) induced turbulence might significantly contribute to fast ion stopping. However, we notice that the evolution of the temperature of fireball electrons and, therefore, heat conduction issue depend on electron-ion coupling during fireball expansion.

iii) Blast. For the energies of D/T ions in the blast ~ 100 keV (see for example [3]) and residual neutral hydrogenic gas density $\sim (1-10)\times 10^{19}\,\mathrm{m}^{-3}$, it is not feasible to slow blast down due to binary collisions. However, even small fraction of the blast energy going to residual gas/plasma causes significant plasma heating and ionization of the gas.

Conclusions. We show that the residual density of the gas/plasma mixture in ~10 m radius chamber can be rather high, $n \sim (1-10)\times 10^{19}\,\mathrm{m}^{-3}$, just due to pumping limitation. This 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 while the radiation is very effective in gas/plasma energy dissipation for the temperatures ~few eV, it does not work for sub eV temperatures. Heat conduction mechanism is not fast enough either. Therefore, it is difficult to expect that averaged temperature of gas/plasma mixture can be reduced to sub-eV level between the shots. It is often assumed that plasma is almost completely extinguished between the shots. However, this may be not the case, due to relatively high temperature of gas/plasma mixture three-body recombination becomes ineffective for residual plasma density below $\sim 10^{19}\,\mathrm{m}^{-3}$ and plasma diffusion likewise heat conduction is not fast enough either. As a result, expected residual plasma density is about $n_{pl} \sim 10^{19}\,\mathrm{m}^{-3}$. 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. We find that potential energy released on the target due to surface recombination of atomic and plasma species can significantly exceed the heat flux due to just kinetic energy. However, residual plasma might help in stopping of fast ions from the fireball by triggering collective plasma interactions. Finally we notice that the temperature of the gas/plasma mixture 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.

Acknowledgments. Supported by the US DoE grant DE-FG03-00ER54568 at UCSD.

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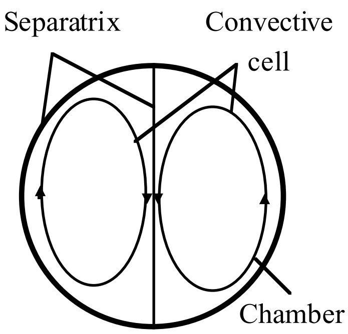

Fig. 1. The convective sell.

$T \setminus n_{pl}$	$10^{18}\,\mathrm{m}^{-3}$	$10^{19}\,\mathrm{m}^{-3}$	$10^{20}\,\mathrm{m}^{-3}$
0.2 eV	~ 0.1 s	$\sim 3\times10^{-3}$ s	$\sim 10^{-4}$ s
0.6 eV	~ 0.8 s	$\sim 5\times10^{-2}$ s	$\sim 2\times10^{-3}$ s
1.2 eV	~ 2 s	~ 0.15 s	$\sim 10^{-2}$ s

Table 1. Characteristic plasma recombination time, τ_{rec}.

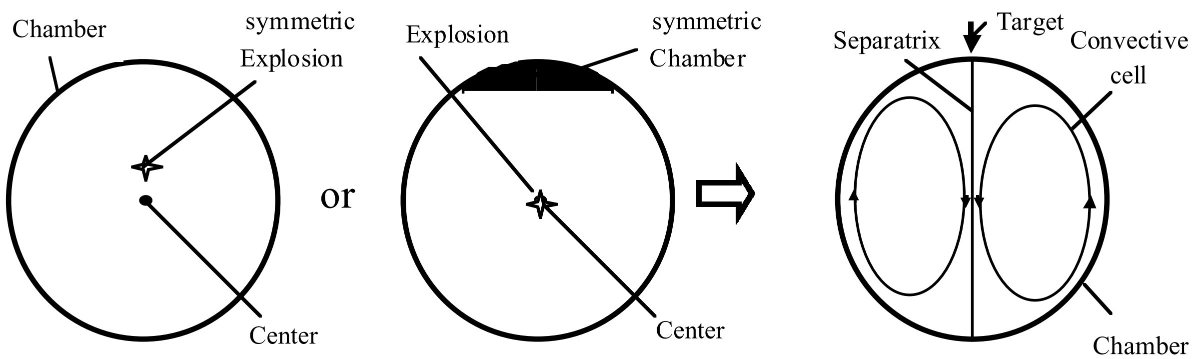

Fig. 2. Formation of convective cell.