HEIGHTS INTEGRATED MODELING OF DIVERTOR RESPONSE DURING ELMs

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OUTLINE

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III. **Modeling SOL plasma during ELMs**

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I. Introduction

- **Tokamak opeartion in enhanced confinement mode is an ELMy regime.**

- **Particles and energy fluxes with magnitudes of up to 10 % of core plasma thermal energy is released in time ≈1 ms.**

- **ELMs play an important role in operating at rather high density and in removing He ash and impurities.**

- **However, ELMs can cause contamination of core plasma by vaporized and sputtered particles from the divertor plate. Can terminate plasma in a disruption in future Tokamaks.**

- **Need to study structure of SOL during ELMs to define from of energy reaching divertor surface and dynamics of interaction of SOL particles with divertor material.**

Characteristics of ELMs

In Comparison to Disruptions

- **Much more frequent and must be tolerated**

- **Much lower energy density about 1-2 MJ/m^2**

- **Deposition time is about 1 ms.**

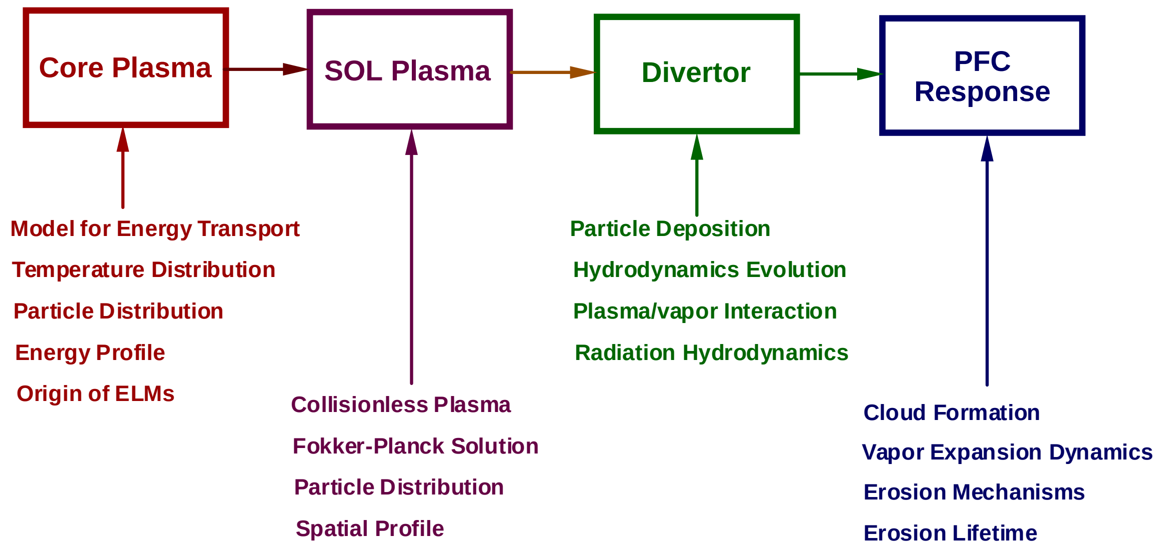
- **Complicated physics:**

    - **Lower density vapor cloud**
    - **Higher cloud temperature**
    - **Mixing effects of vapor and plasma**
    - **Higher velocity of vapor expansion**

- **For reactor conditions ELMS can be very serious and should be studied in detail.**

- **Disruptions in current Tokamak machines (e.g., DiMES) may simulate ELMs in future large Tokamaks.**

Modeling Stages of ELMs in HEIGHTS



Hassanein (ANL)

Common Features of ELMs

- **During ELMs part of plasma energy, $Q_{ELM} = \eta Q_{core}$, escapes through SOL to diveror plate. Fraction η is ≈ 1-10%.**

- **Duration of ELMs is $0.1 < \tau_{ELM} < 1$ ms, but usually most ELMs duration close to $\tau_{ELM} \approx 1$ ms.**

- **The ELM energy to SOL consists of conduction energy due to thermal conduction and convection energy carried by diffusing particles.**

- **The core plasma escaping to SOL due to MHD instabilities during ELMs is lost within a volume between radii R_{ELM} to R_s.**

$$V_{ELM} = \pi(R_s^2 - R_{ELM}^2), \quad N_{ELM} = \int_{R_{ELM}}^{R_s} N_i(r) 2\pi R \cdot 2\pi r \cdot dr,$$

$$Q_{ELM} = \int_{R_{ELM}}^{R_s} \frac{3}{2} k \left(T_i + Z_{eff} T_e\right) N_i(r) 2\pi R \cdot 2\pi r \cdot dr$$

$$= \frac{3}{2} k T_{mean} \left(1 + Z_{eff}\right) \cdot N_{ELM}, \quad T_{mean} = \frac{2 Q_{ELM}}{3k\left(1 + Z_{eff}\right) N_{ELM}}$$

II. Core and SOL plasma at normal operation

- **Spatial distribution of temperatures (T_e and T_i) and density N in core plasma from center (r = 0) to separatrix (r = R_S) can be approximated by the following fit formula:**

$$T_i(r) = T_0(1-\alpha z), \quad z = \frac{r}{a}, \; \zeta = \frac{z - z_b}{\Delta z_b}, \; \alpha = 0.8,$$

$$T_e(r) = (T_0 - T_s)(1-\alpha z)\frac{(1 - th\zeta)}{2} + T_s$$

$$N_i(r) = (N_0 - N_s)(1-\alpha z)\frac{(1 - th\zeta)}{2} + N_s$$

- **The width of the thermal barrier zone is scaled from current tokamak devices such as DIII-D to future ITER-like machines.**

Collisionless SOL Model

- **In collisionless SOL plasma the edge plasma acts an electrostatic trap for electrons, since electrons which originally have parallel energy $E_{||}$ lower than wall potential energy eφ, $E_{||} < e\varphi$, will be trapped between inner and outer divertor plates.**

- **A solution is developed from Fokker-Planck equation for electron distribution and balance in the SOL. Distribution of trapped electrons has the form:**

$$F = \frac{1}{(2\pi)^{3/2}} C_q e^{-\frac{p^2}{2}} \left[1 - ap + \frac{1}{3} ap^3 + \frac{\sqrt{2\pi}}{2} e^{\frac{p^2}{2}} \Phi(p) \right]$$

- **The ion charge in SOL is mainly neutralized by the trapped electrons.**

- **Particle flow to divertor plates consists of hot ions beam, $E_I = T$, hot-escaping electrons, $E_{||} \geq e\varphi$, and slow diffusing electrons with energy, $E_{trap} \approx 0$.**

- **Electron distribution in the SOL includes four different electron beams (two hot electron beams and two cold electron beams). Existence of such beams can result in two-stream electron instability thus the SOL plasma can be turbulent.**

Equation of State for Mixture (EOSM)

- A set of kinetic equations for charge distribution are solved

$$\frac{dn_{z,j}}{dt} = -\alpha^{ion}_{z,z+1} n_{z,j} n_e + \alpha^{ion}_{z-1,z} n_{z-1,j} n_e + \alpha^{rec}_{z+1,z} n_{z+1,j} n_e$$
$$-\gamma^{photo}_{z} n_{z,j} + \gamma^{photo}_{z+1} n_{z+1,j} + \gamma^{photo}_{z-1,j} n_{z-1} - \alpha^{ion}_{z,z+1} n_{z,j} n_{e,beam}$$
$$n_e = \sum_j Z(j) n_j$$

where ***j*** is D, T, He, or Li, Z(***z,j***) is charge of z ion of element ***j***, coefficients α, β, γ are rates of ionization, recombination, and photo-processes respectively. Direct ionization by incoming beam is taken into account by last term.

- Energy and pressure of this mixture are defined as

$$E = \sum_j \sum_z \left[\frac{3}{2} kT\left(1 + Z(j)\right) + I_\Sigma(j) \frac{n_{j,z}}{n_j} \right] n_j, \quad I_\Sigma(j) = \sum_0^z I_z(j),$$
$$P = \sum_j kT\left[1 + Z(j)\right] n_j$$

- Hydrodynamic equations are solved using average Z* and mass A* approximation:

$$Z^* = \sum_j \frac{Z_j n_j}{n}, \; A^* = \sum_j \frac{A_j n_j}{n}, \; n = \sum_j n_j .$$

Radiation of Mixture

- The level population of each ion of each element is calculated by use also a set of kinetic equations

- Population of upper level is found by solving the rate equations:

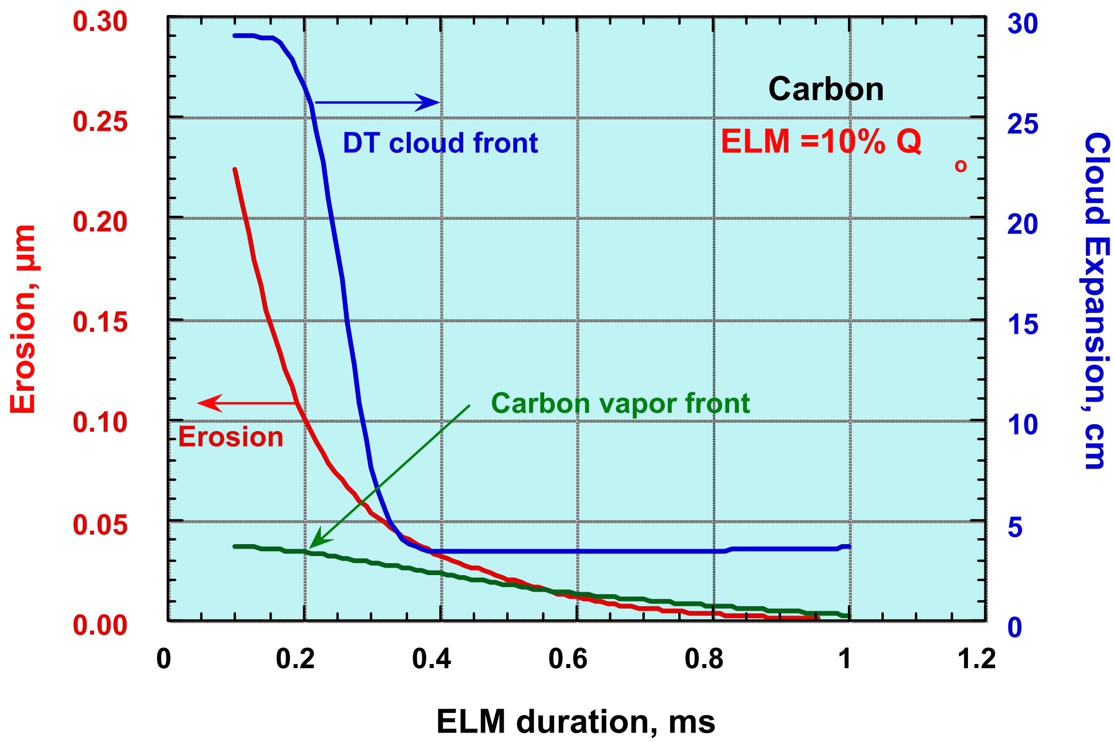
$$\frac{dn_{z,l}}{dt} = -\alpha_{z,l}^{ion} n_{z,l} n_e + \alpha_{z+1 \to z,l}^{rec} n_{z+1} n_e$$

$$-\gamma_{z,l}^{photo} n_{z,j} + \sum_{m<l} \gamma_{z,m}^{photo} n_{z,m} + \gamma_{z+1 \to z,l}^{photo} n_{z+1},$$

Here it is assumed that ionization, photo-excitation, and photo-recombination for lower Z ions and higher Z ions are summed over all levels.

- In case of large radiation power when induced radiation and contribution of excited levels should be taken into account previous equations are solved simultaneously by iteration on electron density and radiation power.

HEIGHTS Calculations of Material Erosion and Cloud Expansion during ELMs



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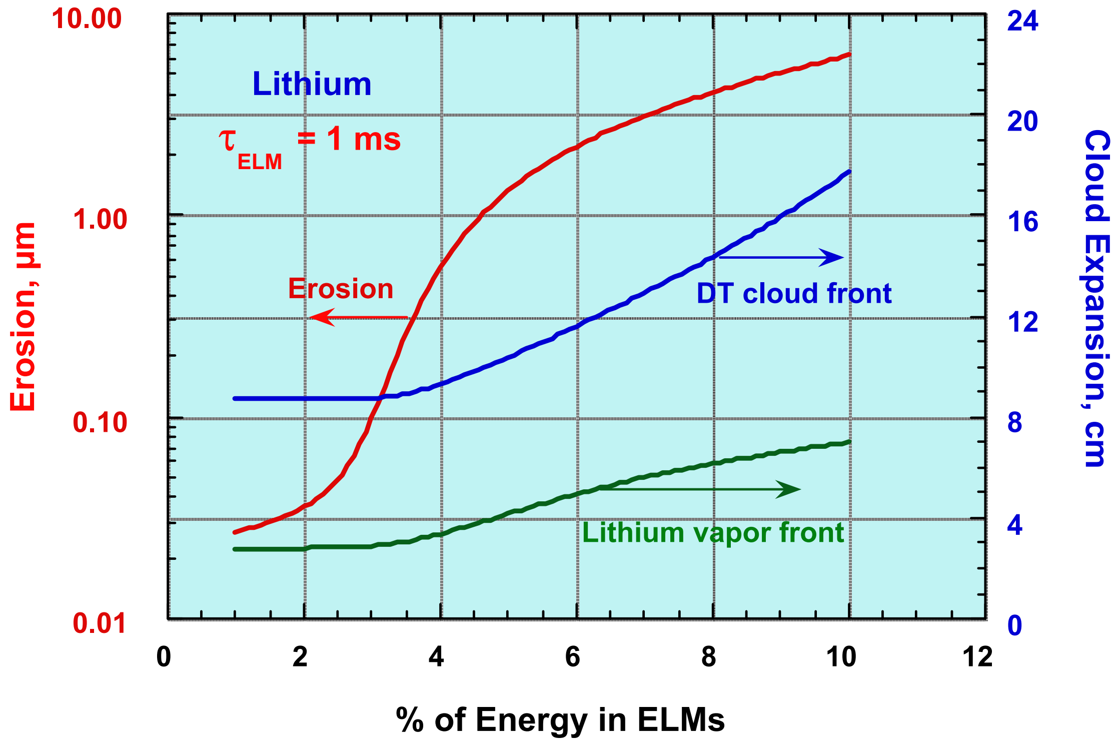


NSTX Parameters

R = 85.4 cm, a = 67.8 cm, V_o=12 m^3 (7.85 m^3), Elongation: 1.6 < k <2.2 (2.2)
Triangularity: 0.2< δ <0.5, I_p = (1-1.5) MA (1.07 MA),

B_z = (3-6) kG (4.5 kG), $B_\varphi(a)$ = 2 kG,

Inclination of magnetic lines: $\alpha_\mu(a) = \text{arctg}\,(B_\varphi / B_z) = 24°$ (0.42 radian)
Inclination to divertor plate: $\alpha_d(a) = 90°$ (1.57 radian)

β_T = 25 % (22%), W_{plasma} = 5 MW (3.2 MW), W_{HHFW} = 6 MW (4.2 MW),
τ_E = 500 ms (120 ms), n_e= (1-6)·10^{19} m^{-3} (4·10^{13} cm^{-3}), $T_{e,I}$ = 2 keV (0.8 keV),

$P = n_e k T_{e,I}$ = 0.134 atm, P_μ(4.5 kG) = 0.81 atm
Z_{eff} = 3, size of divertor plate $L \approx 5$ cm

Total number of particles N_{core}=2·10^{20},
Temperature of plate T_{d0} = 520 K

ELM Parameters

τ_{rise} = 0.7 ms , τ_{fall} = 1.6 ms, τ_{total} = 2.3 ms ($\tau_{1/2}$=1.15ms)

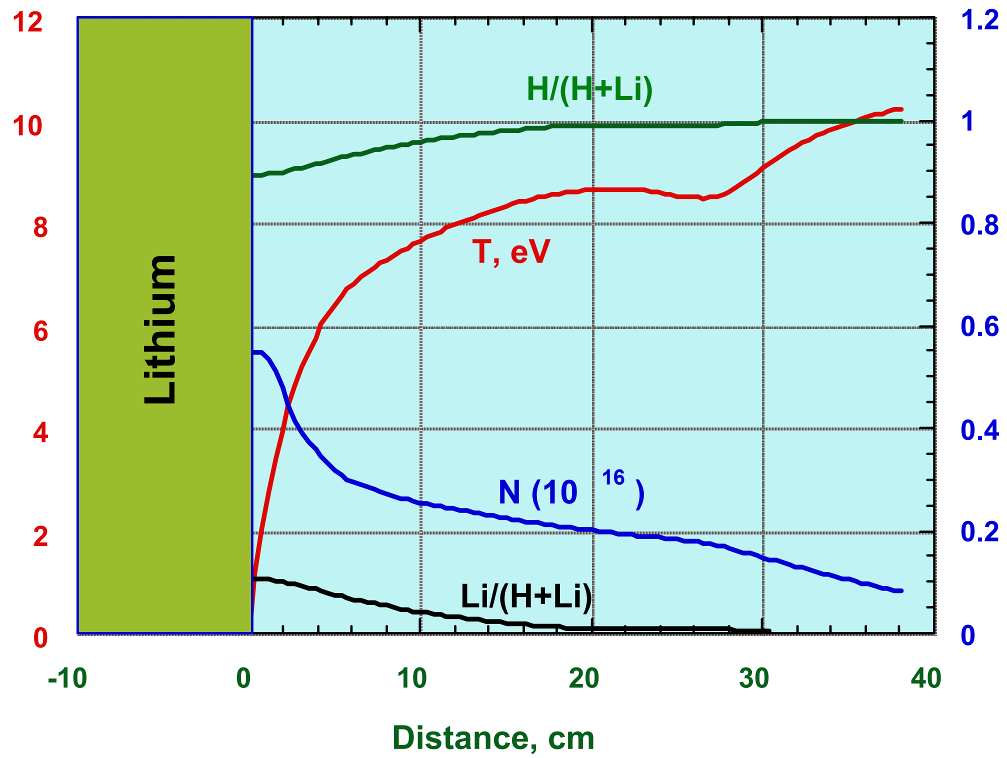
(f = 130 Hz, $\Delta\tau = f^{-1}$ = 7.7 ms), $\frac{\Delta W}{W} = \frac{\Delta Q}{Q} = \frac{(3-5)\,kJ}{180\;kJ} \approx 2\%$,

Particles flux to SOL during an ELM is $N_{ELM} = 10^{19}$,

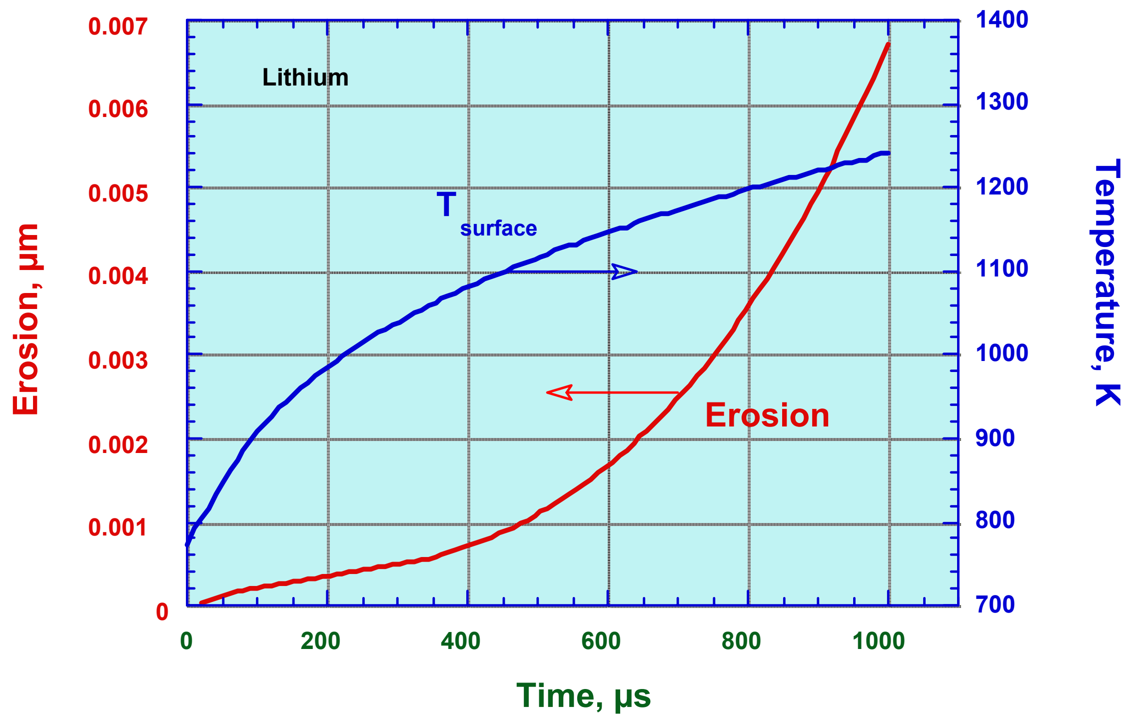
Energy to SOL during an ELM is Q_{ELM} = 3.6 kJ,

Diffusion coefficient $D_\perp \approx 0.25 m^2/s$,

HEIGHTS Calculations of Vapor Cloud Evolution in NSTX during an ELM



HEIGHTS Calculations of Erosion Thickness of NSTX Module during an ELM



VI. Summary

- **ELMs can be a serious concern for plasma-facing components during normal operation of next generation tokamaks.**

- **Two-fluid model is developed to integrate SOL parameters during ELMs with divertor surface evolution using HEIGHTS numerical simulation package.**

- **HEIGHTS indicate that there exist an ELM power threshold for each divertor material at which the periodic pulses of energy cause excessive target erosion and large vapor expansion.**

- **Large vapor expansion leads to plasma contamination and possible termination in a disruption even in renewable surface materials such as lithium where erosion is not a problem.**

- **Excessive erosion from vaporization and macroscopic particles/droplets formation may affect subsequent plasma operations and lead to much shorter lifetime in non-liquid surfaces.**