Study on xenon ionization dynamics and efficiency of capillary discharge EUV source*

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* This work is partly supported by NEDO (New Energy and Industrial Technology Development Organization) and EUVA (Extreme Ultraviolet Lithography System Development Association)

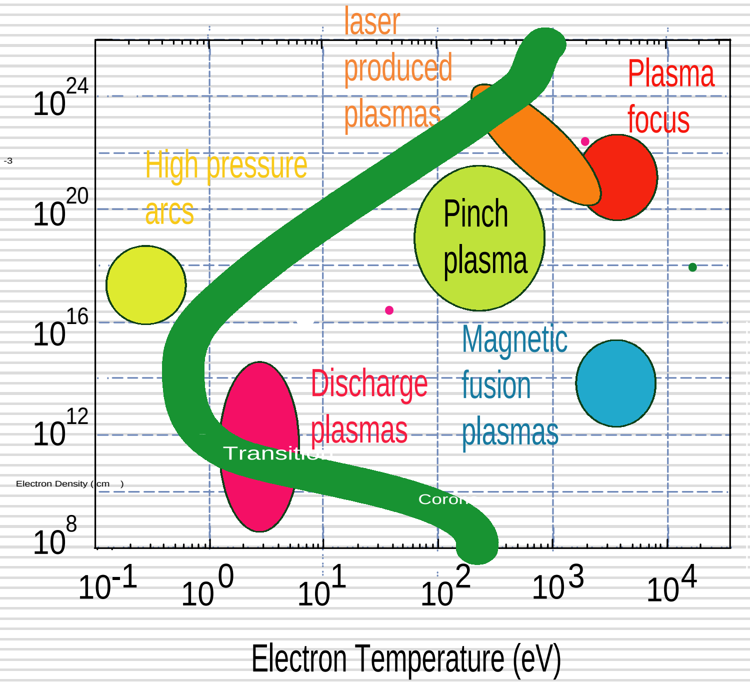
3RD International EUVL Symposium, Japan

Tokyo Institute of Technology

Abstract

- The characteristics of the plasma conversion efficiency of xenon have been theoretically investigated using a collisional radiative model. In relation to rapid plasma heating in capillary discharges, the influence of non-equilibrium ionization on the conversion efficiency has been investigated. The study clearly shows that the ionization state distribution is a function of the history of plasma evolution, and a rapid heating process under appropriate plasma conditions allows us to obtain higher conversion efficiency values compared with the steady-state calculations.

- In the pinch plasmas* heating & cooling times are an order of nanoseconds. These plasmas tend to be transient.



- * D. Atwood, Soft X-Ray And Extreme Ultraviolet Radiation (Cambridge University Press, 1999).

• Calculations

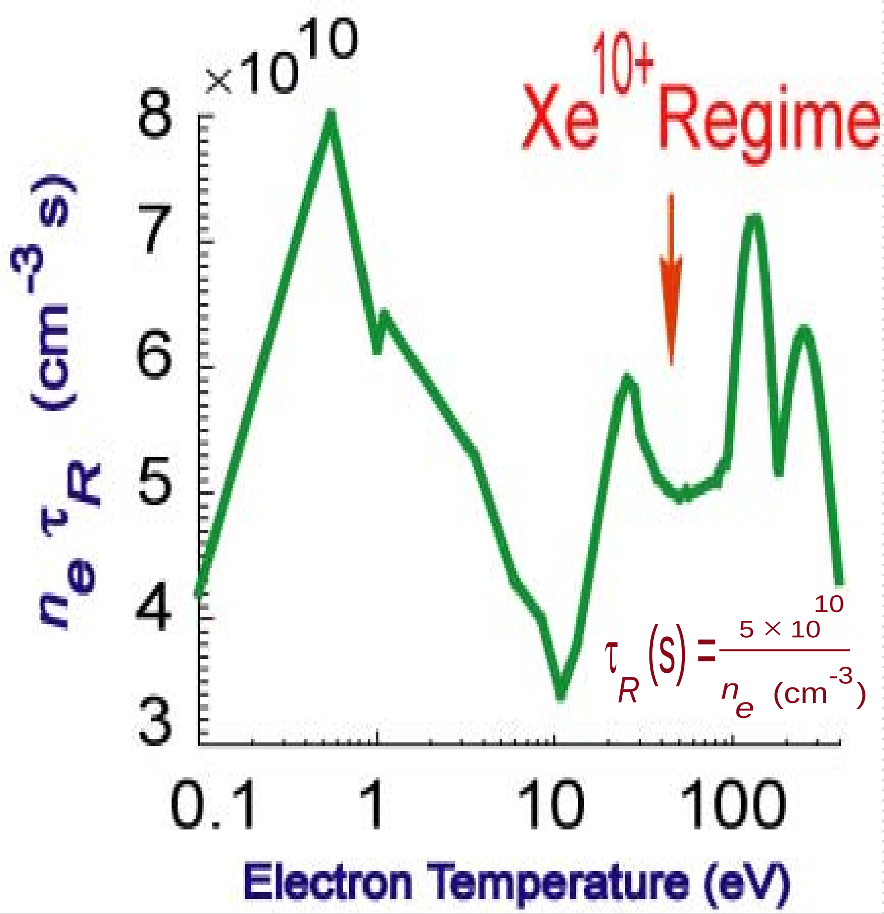
- Relaxation time of ground states (the time which partially charged xenon ions must spend before reaching to the collisional radiative equilibrium) & Average ionic charge state

- Population of excited states is investigated using collisional radiative model (necessary atomic data: HULLAC atomic code)

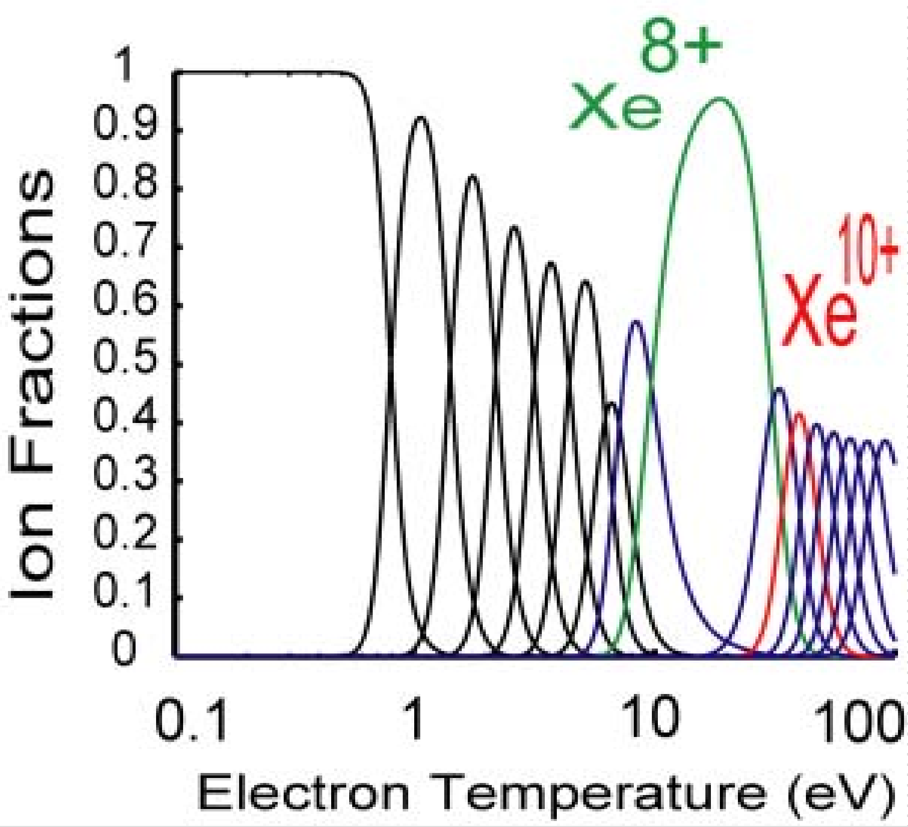
- Plasma conversion efficiency

• Relaxation time* of xenon

- Relaxation time shows that there are delay times of charge states compared to steady-state plasma in ionization & recombination phases in discharge plasmas.



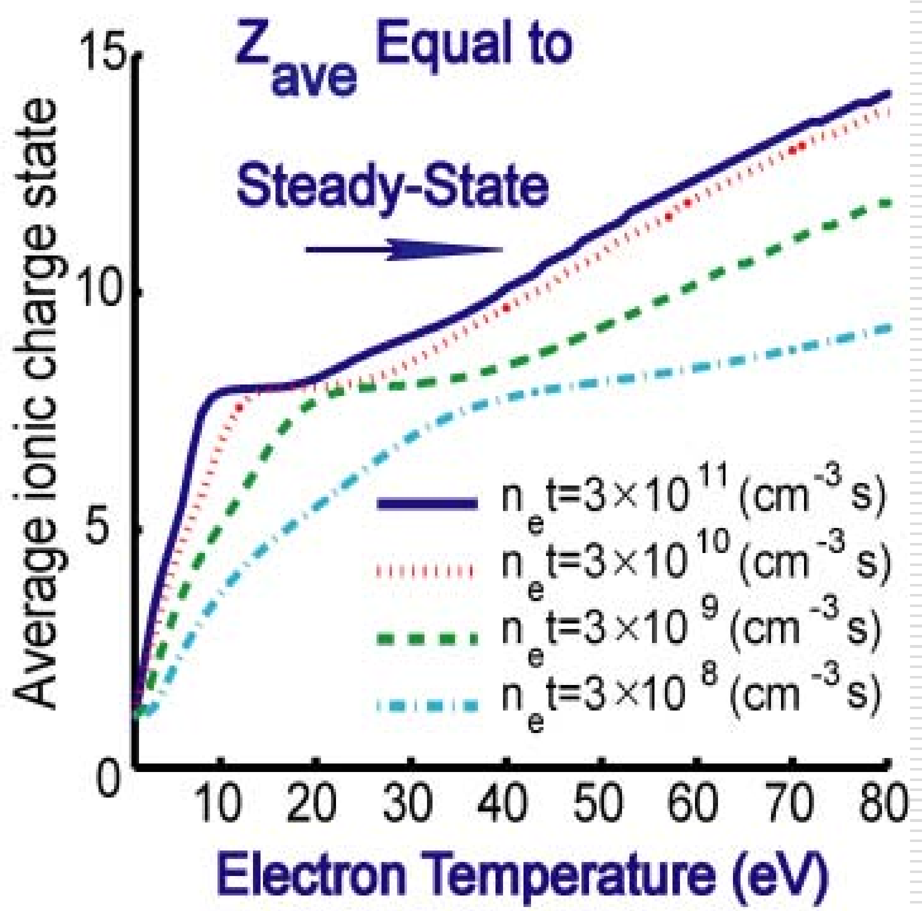
- Steady state ionization balance (time longer than relaxation time).



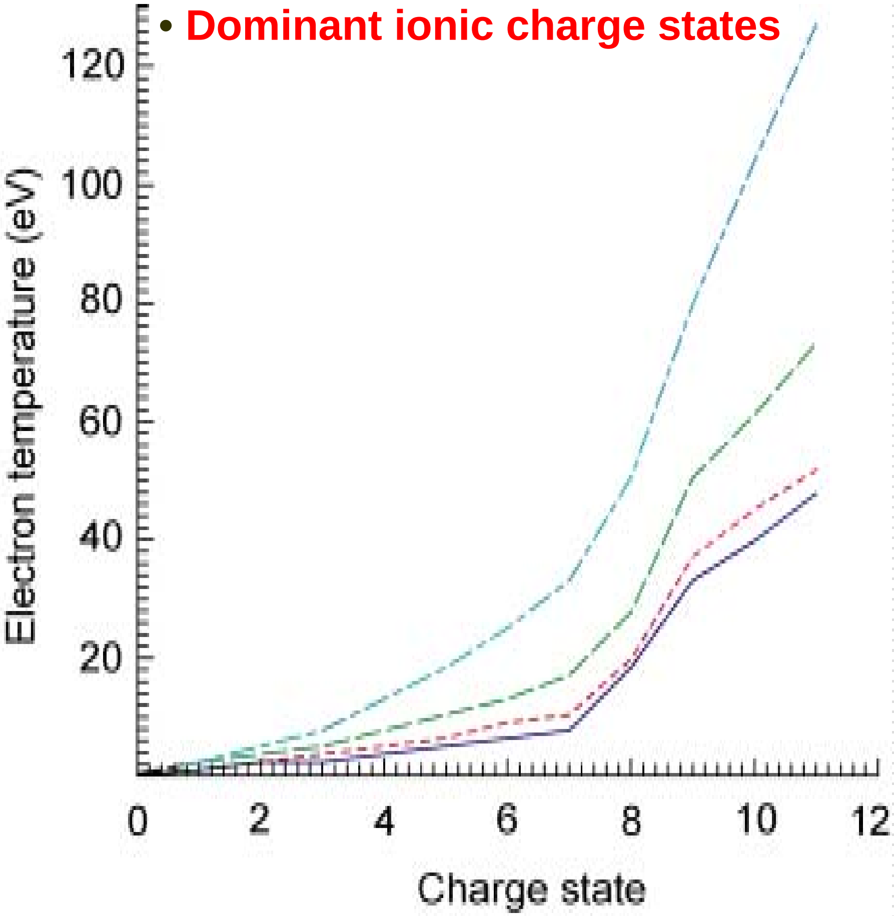
*M. Masnavi *et al.*, J. Appl. Phys. 95 (2004) 434.

• Average ionic charge state

• Charge states shift to higher temperature compared to steady state ionization balance, if product of electron density and heating time are smaller than the relaxation time.



• **Dominant ionic charge states**



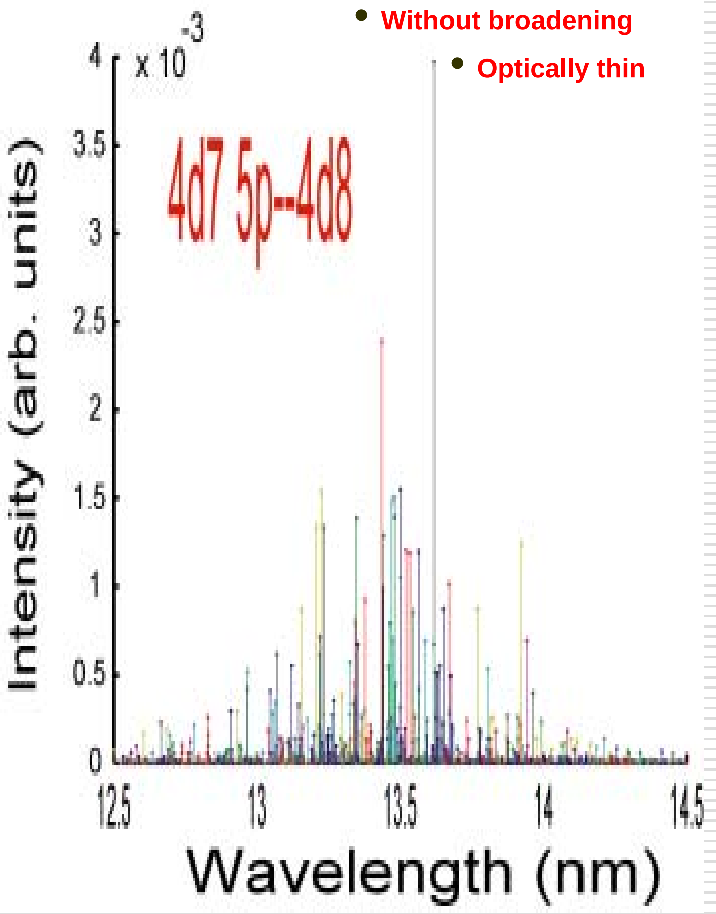
Problem:

Higher temperature → shorter ionization time → shorter emission duration

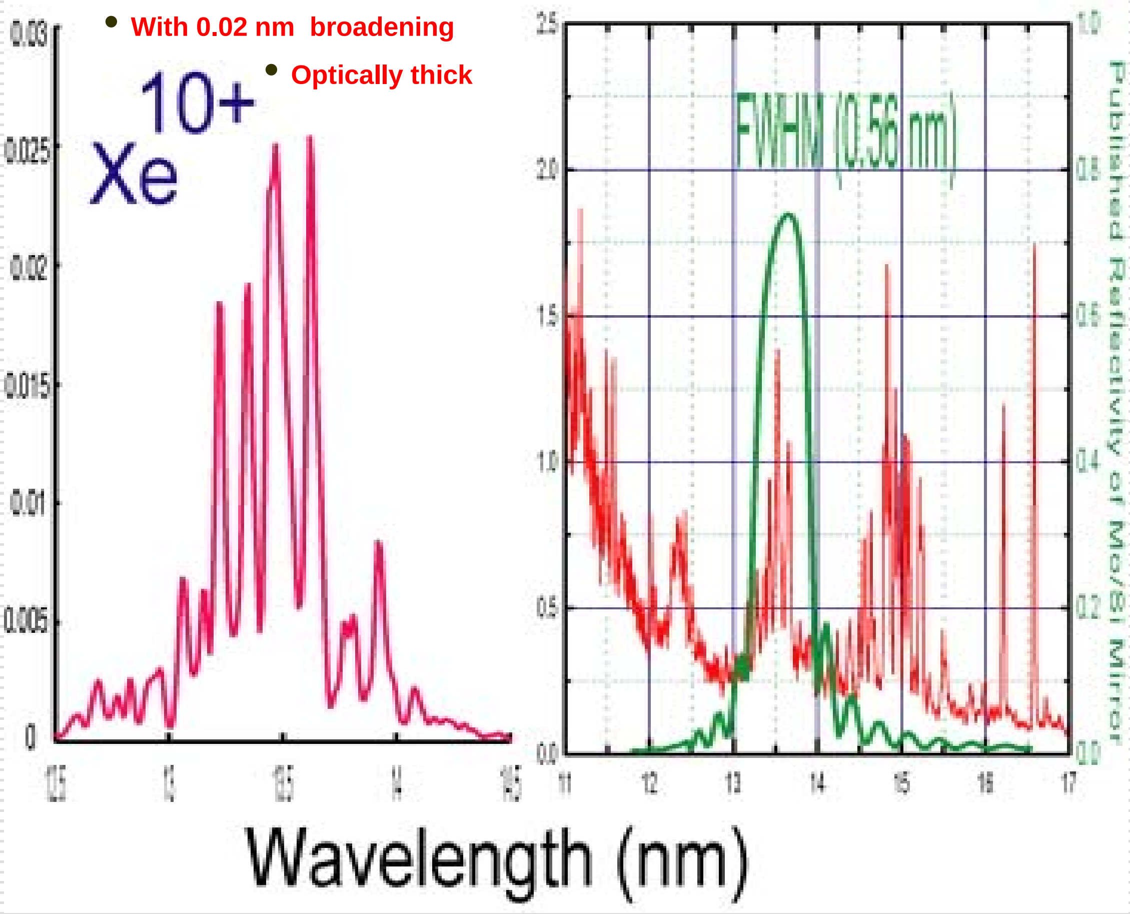
Typical xenon spectrum

- **Mainly ten-times ionized xenon* radiates in 2% BW (HULLAC atomic data)**

 # Experimental results*



- **Without broadening**
- **Optically thin**



- **With 0.02 nm broadening**
- **Optically thick**

***A. Sasaki, J. Plasma Fusion Res. 79 (2003) 315.**

***Cymer, Phys. Today, Feb. (2002) 44.**

Plasma conversion efficiency

MODEL & ASSUMPTIONS*

- Using steady-state ionization model
- Doppler-opacity broadening for lines
- The integrated spectral brightness for non-LTE plasma with constant source function (HULLAC atomic data to estimate the population of excited states)
- Emission duration: the inertial confinement time*
- Plasma conversion efficiency (PCE): the quotient of the emitted energy in 2% BW and the plasma energy (ionization energy+thermal energy)

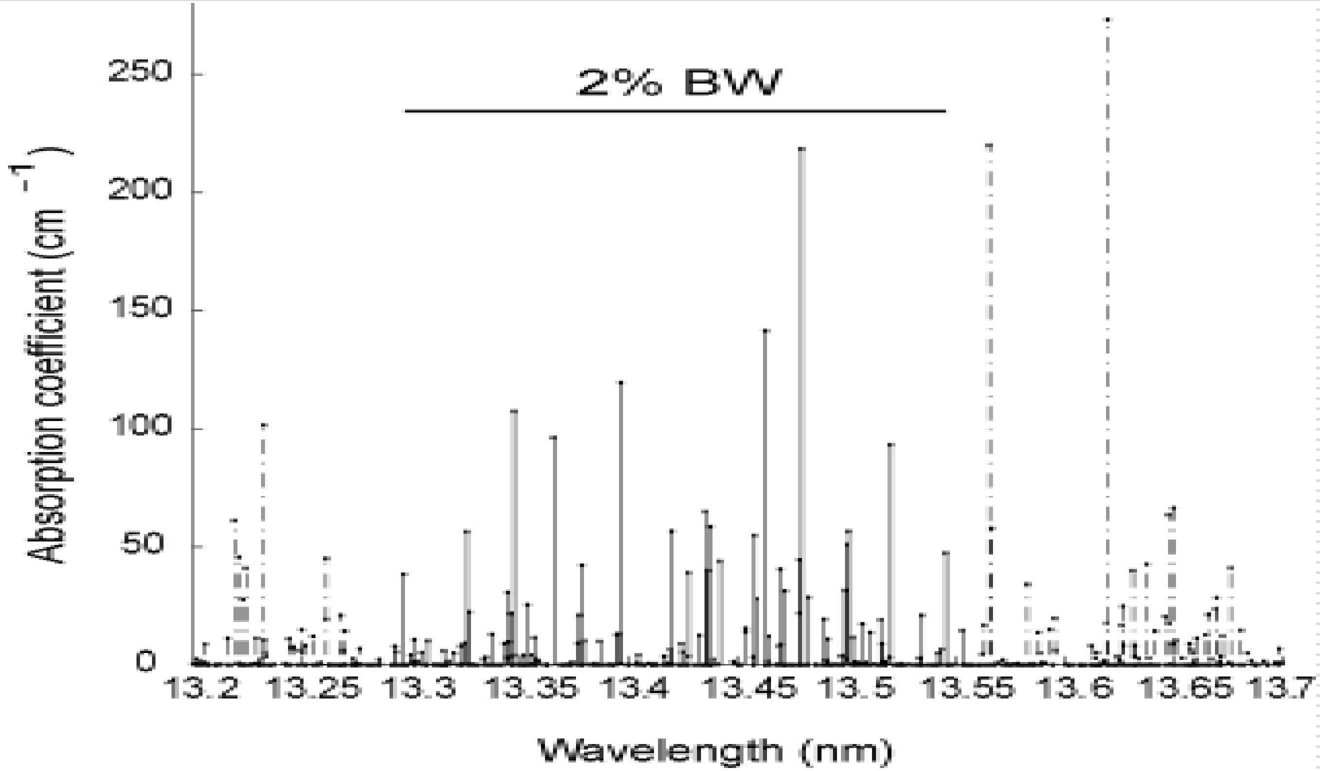
***M. Masnavi *et al*., to be publish in Jpn. J. Appl. Phys.**

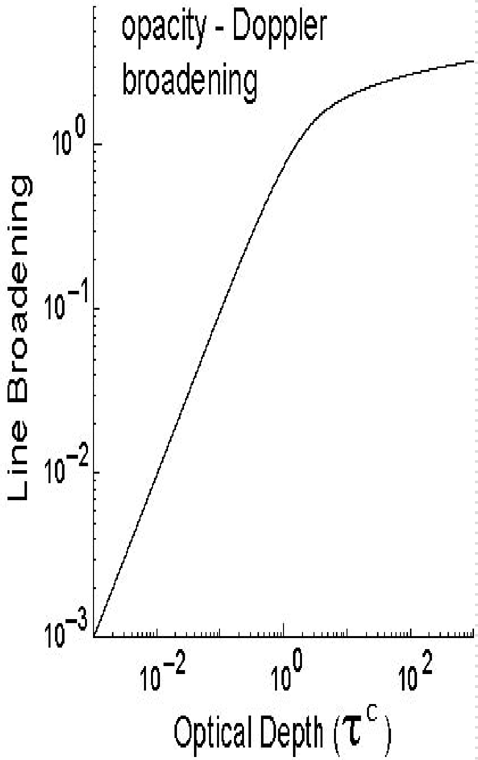
***R. Lebert *et al*., Proc. SPIE 4343 (2001) 215.**

Absorption coefficient & Broadening

- For typical plasma dimension of 0.015 cm, plasma is optically thin for most of transitions in 2% BW

- Simple broadening: low-density: Doppler broadening

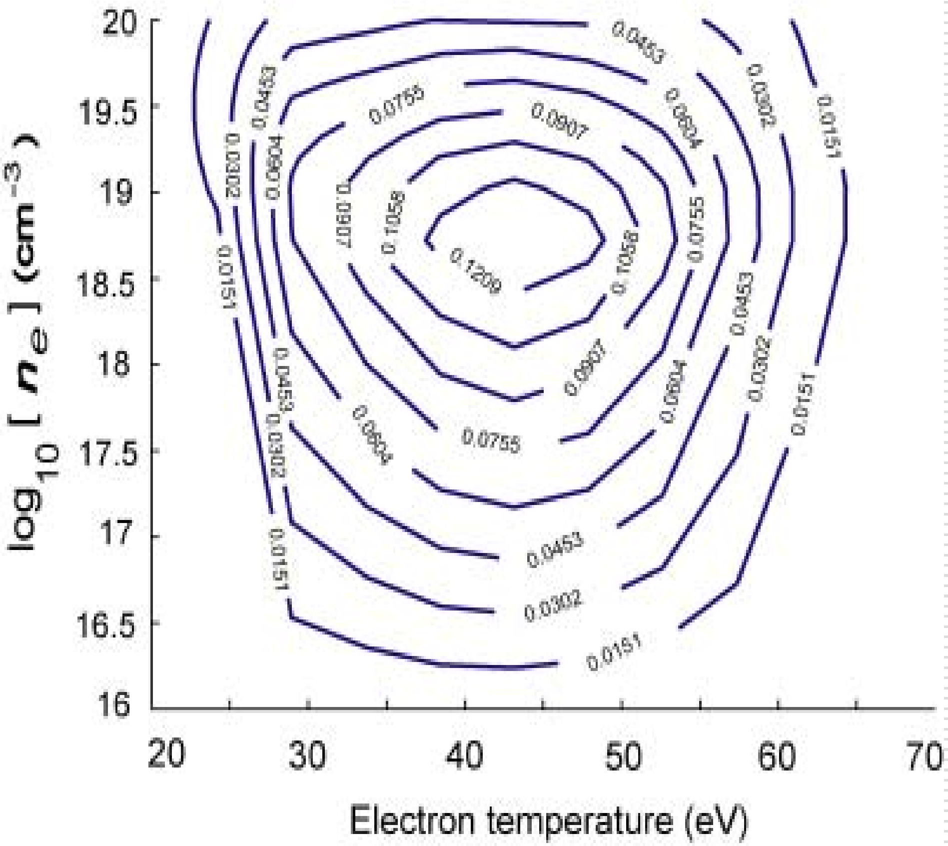




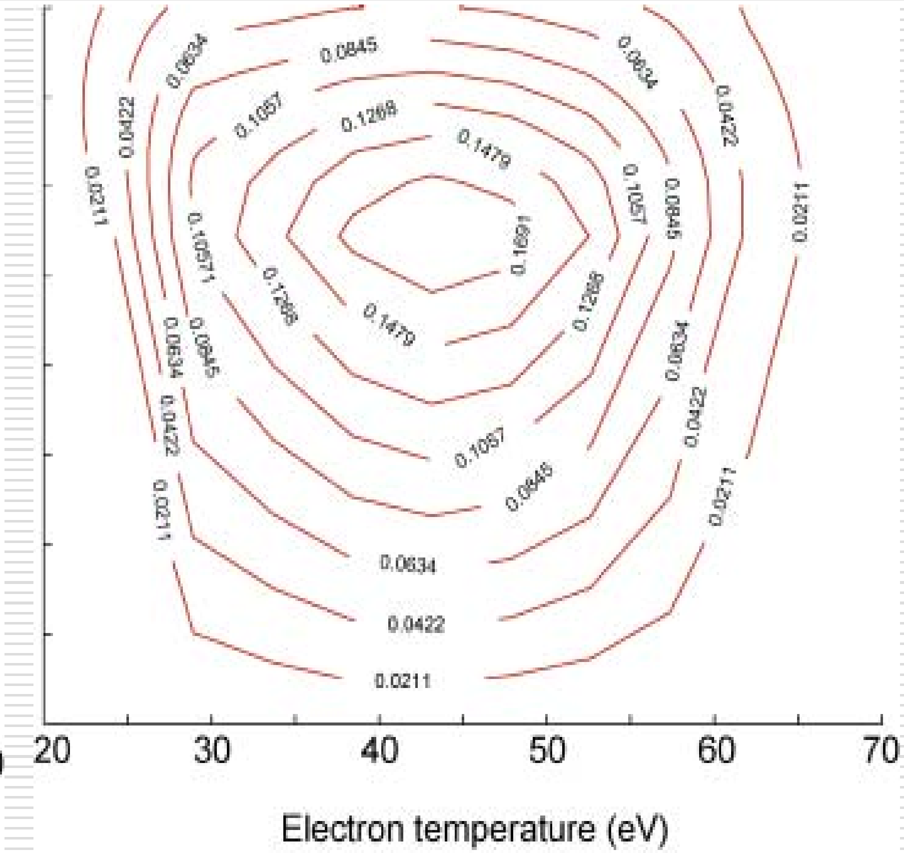
• PCE (% /sr within 2% BW)

- **Plasma length: 0.1 cm**
- **Optical depth is calculated based on plasma radius**

• **Plasma radius=0.015 cm**



• **Plasma radius=0.02 cm**

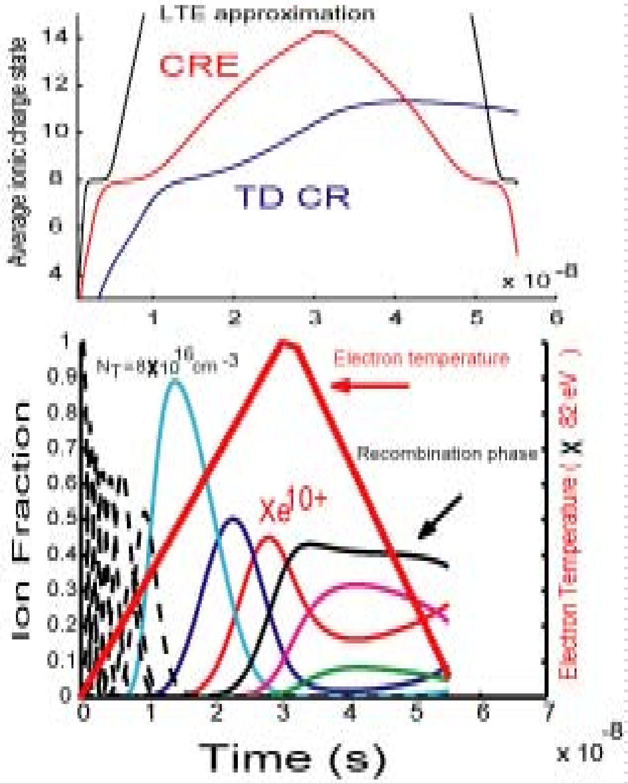


• **Larger radius → higher opacity → higher PCE due to saturation of resonance lines**

• Typical non-equilibrium ionization

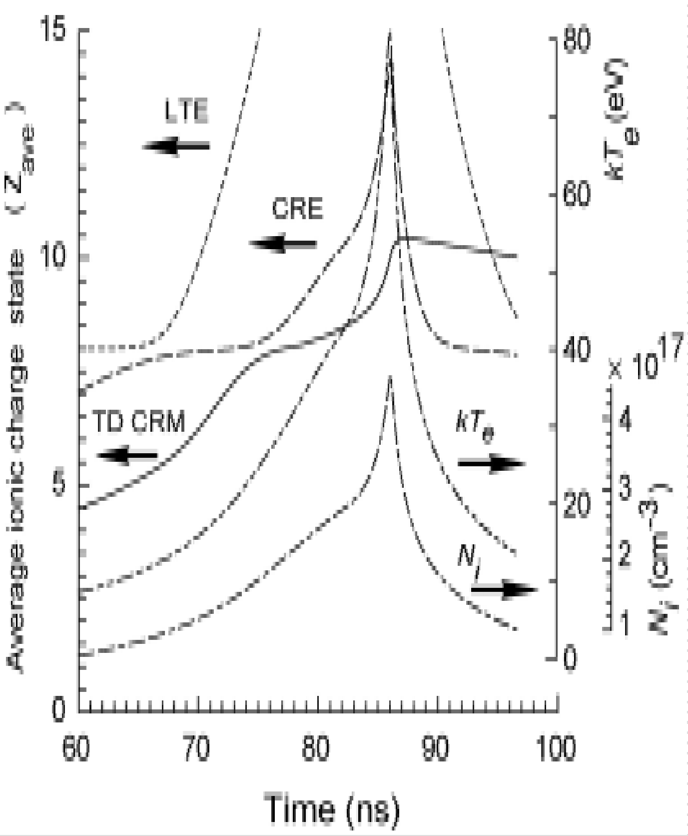
- **Typical examples: Different behavior of charge states in low density & fast heating or cooling processes**

- **Simplified assumption for electron temperature, fixed ion density, electron density using average ionic charge state**



- **Different models to estimate average ionic charge state (LTE, CRE: Collisional radiative equilibrium and time-dependent collisional radiative model (TD CRM)). Time delay of charge states in ionization & recombination phases in TD calculation is clear. Due to the time delay in ionization phase, charge states shift to higher temperature. This makes shorter ionization times. Plasma radiates strongly, but at short time. Due to the time delay in recombination phase the recombination times are longer. Emission duration depends on plasma parameters such as electron temperature and density.**

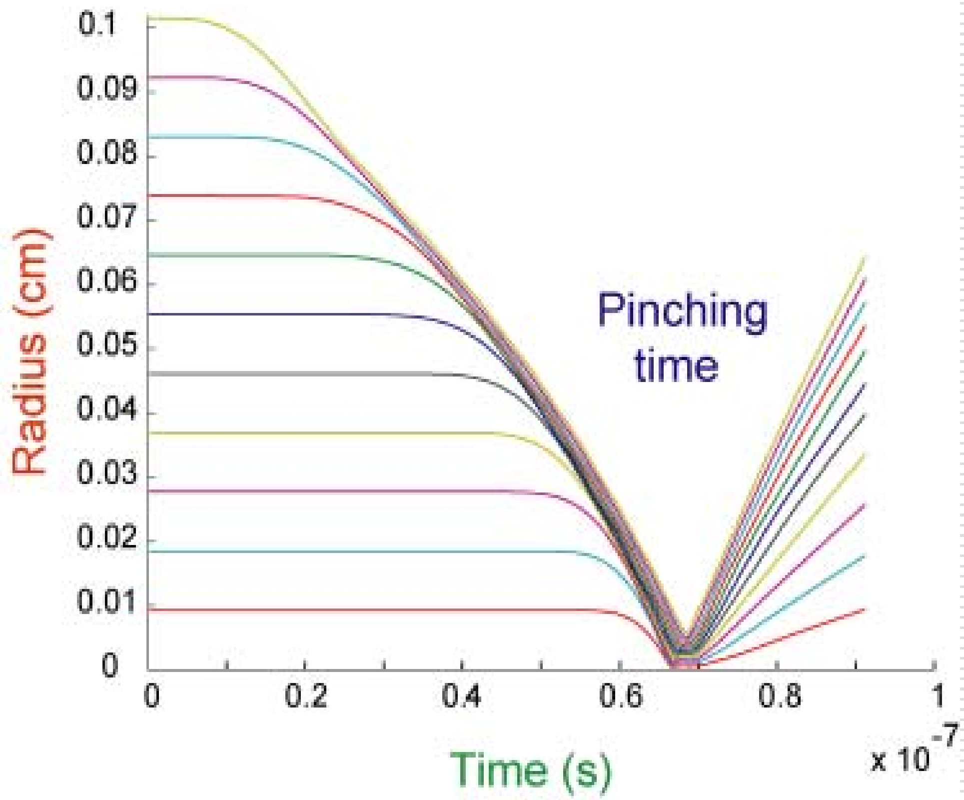
- **Electron temperature & ion density on capillary axis**



Shock heating-capillary discharge

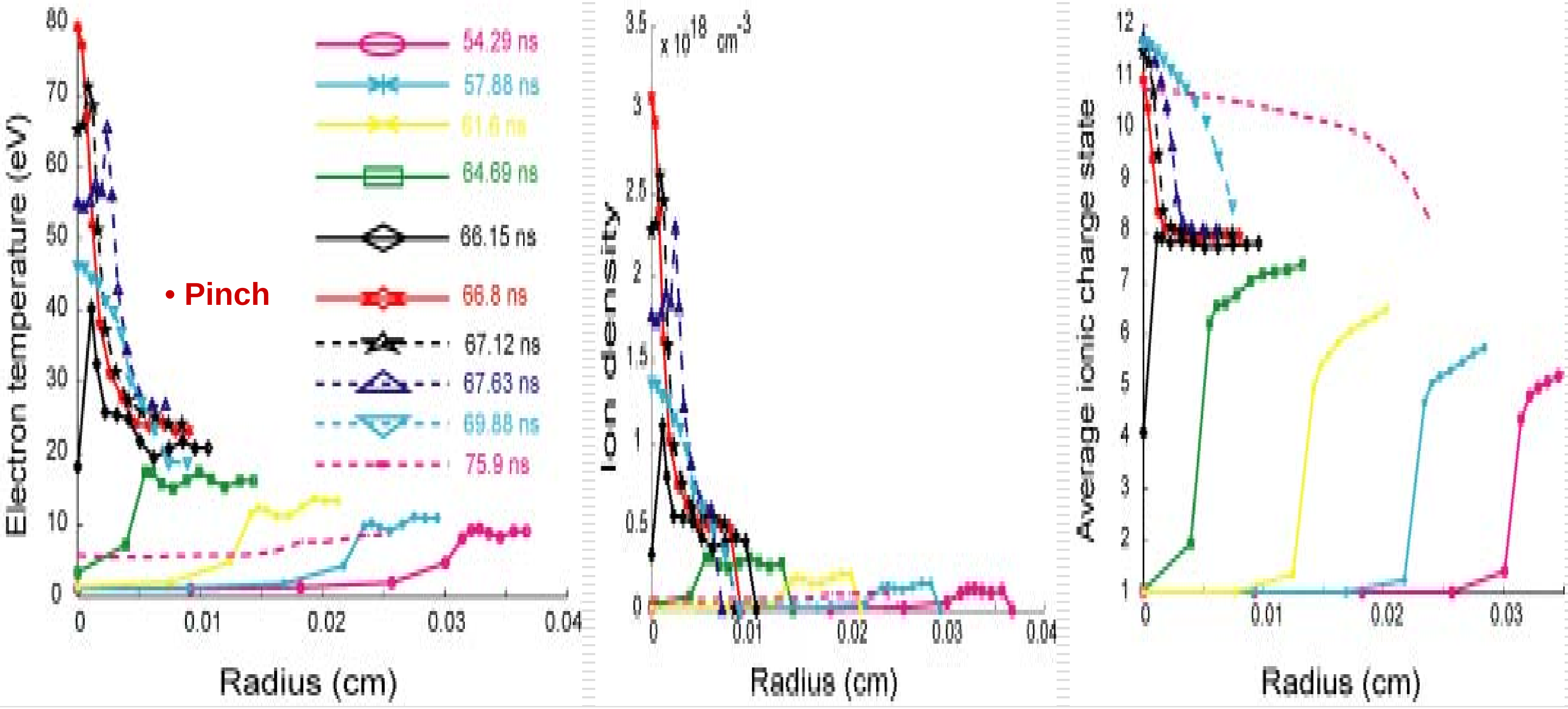
- In capillary discharge major heating process is shock implosion at pinch (fast heating)
- Major cooling mechanism is adiabatic expansion after pinching time (fast cooling)
- Therefore, ionization state distribution is not in equilibrium

- Typical plasma compression in capillary discharge



• Electron temperature & ion density & average ioni charge state

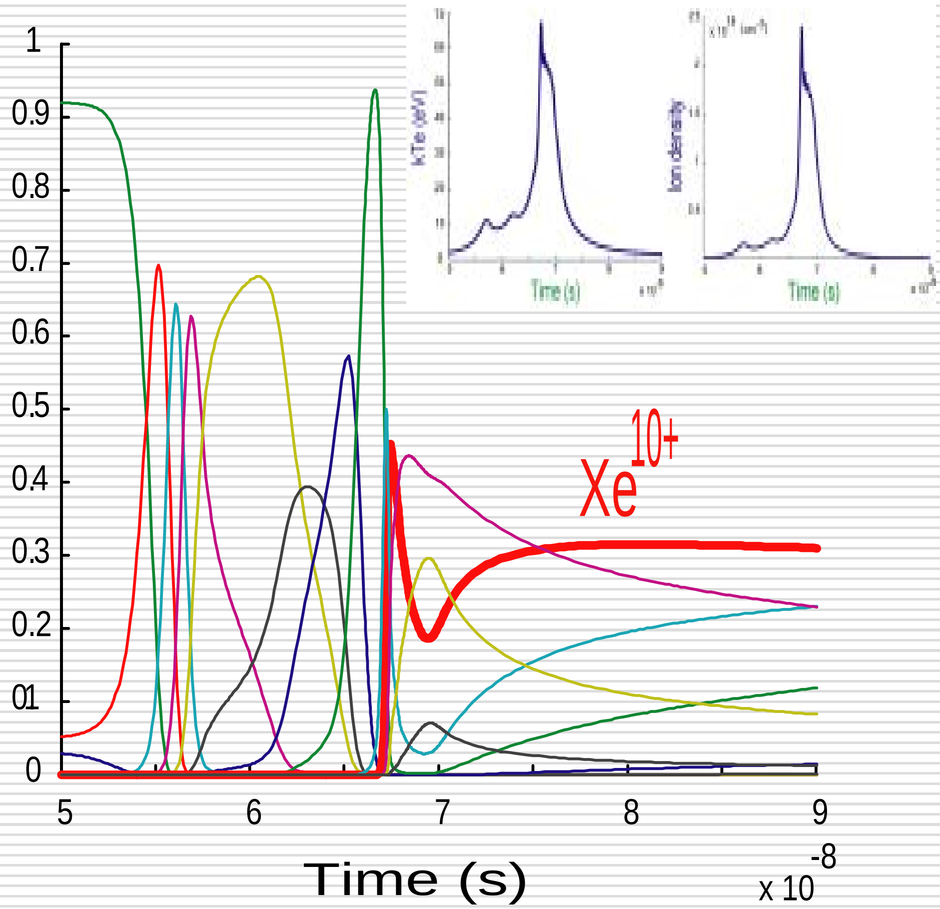
- Before and after pinch
- Freezing of charge states



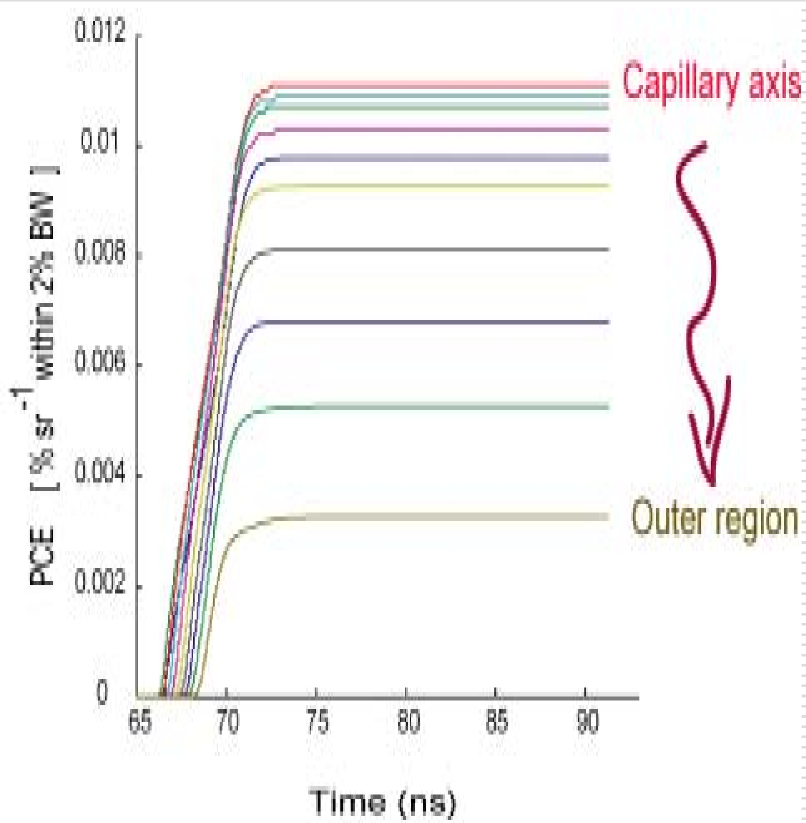
- Pinch

- Maximum ionization occurs after pinching time (maximum temperature)

• Typical ionization states & integrated plasma conversion efficiency



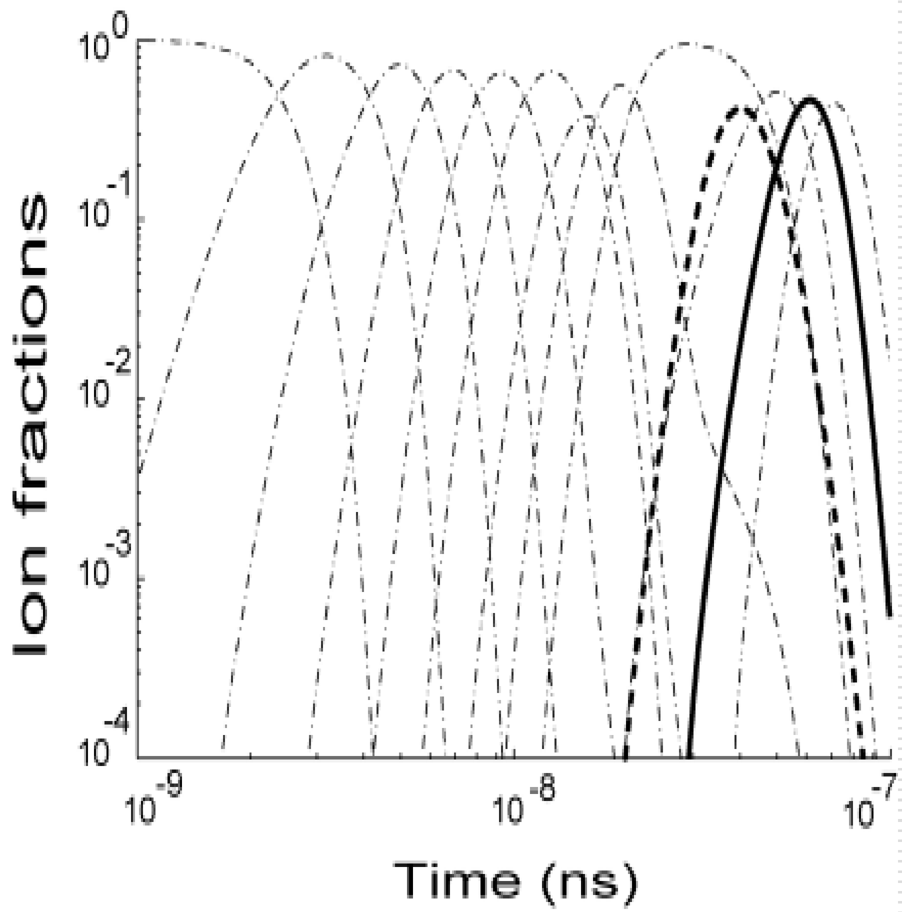
- **Lower PCE in plasma edge (lower charge state & lower opacity)**



- **To increase emission duration may multiple pinch are favorable**

• Plasma conversion efficiency

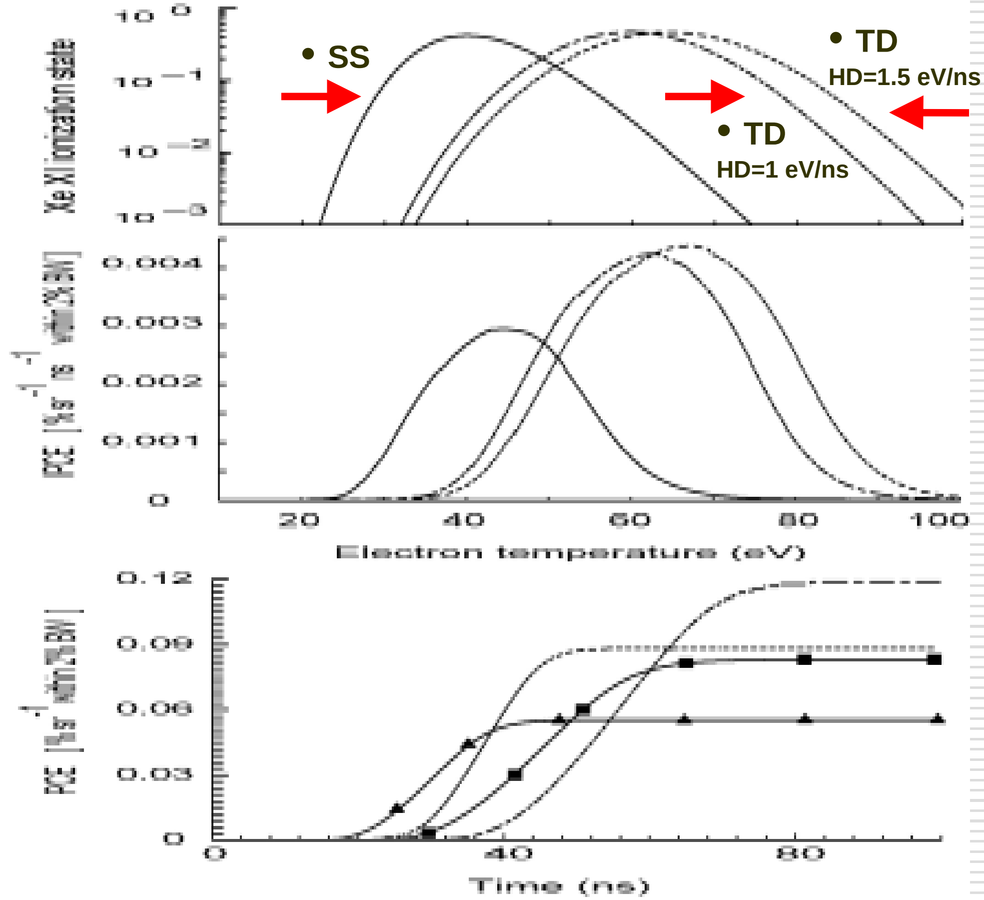
- Simple example
- Ionization phase
- We assumed that the electron temperature increases linearly against time from 0.1 to 100 eV during 100 ns (heating rate = 1 eV/ns)
- Constant total ion density & electron density calculated using average ionic charge
- The bold line is ten-times ionized xenon (Xe XI) in time-dependent calculation (TD) & the bold-dashed line is ten-times ionized xenon but calculated using steady-state CRM



- **Shift to higher temperature → more excitation & radiation → but lower ionization time**

• Plasma conversion efficiency

- Xe XI state in steady-state (solid) and in TD calculation (heating rate (HD) = 1 & 1.5 eV/ns) versus temperature
- Corresponding IPCE: instantaneous plasma conversion efficiency versus temperature
- Total integrated plasma conversion efficiency (PCE) on ionization time against time (solid lines marked by square & triangle correspond to HD = 1 & 1.5 eV/ns in steady-state situation (fast equilibrium condition))



• Shift to higher temperature → higher IPCE → but lower PCE (lower emission duration)

Summary & future works

- Large plasma conversion efficiency is achieved for electron density between 10^{18} and 10^{19} cm^{-3}
- Relaxation time shows that in pinch plasmas charge states are far from equilibrium and the optimum temperature moves to higher value compared to that for steady-state condition
- While non-equilibrium ionization process clearly increases the instantaneous plasma conversion efficiency, an exact scaling of the emission duration is inevitable to maximize the integrated plasma efficiency
- Future investigation will be focused on optimizing conversion efficiency using magneto-hydrodynamic coupled to time dependent atomic kinetics calculations for capillary discharge