Modeling of the Nonequilibrium Plasma of EUV Sources

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Z*

physical model: components & features

Tables (T_e,ρ,Z) for solid matter & for LTE, non-LTE plasmas of ion compositions: EOS; ionization; rates; spectral radiation & transport coefficients

RMHD with energy supply: 2.5D(r,z+φ) plasma dynamics in $(E,B)_{r,\varphi,z}$; nonstationary, nonLTE ionization; multigroup radiation transport in nonLTE with special spectral groups (EUV,laser); solid elements sublimation, expansion

EEMHD in real cylindrical geometry: dynamics of electrons; ionization of weekly ionized plasma (hollow cathode ionization wave)

DPP simulation in real geometry LPP

Spectral postprocessing: 3D ray tracing; detailed spectra

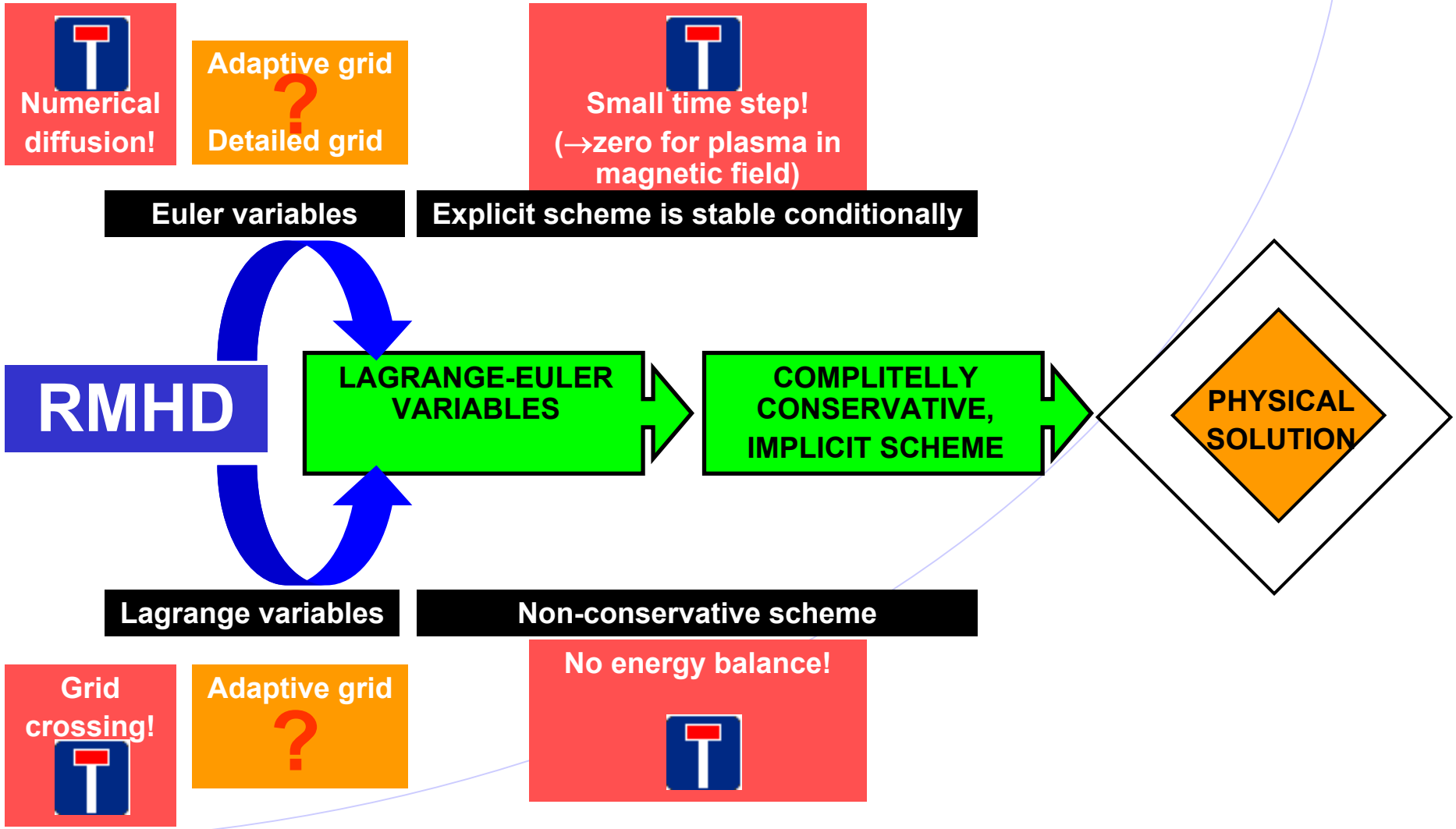
Data: (r,z,*v*,$T_{e,I}$,ρ,*E*, *B*, Z,U_ω, etc); time evolution (I,P_ω ,W, F_ω , etc); visualization

Heat flux postprocessing: element lifetime estimation; fast particle flux

- Improved
- new
- coming

Z*

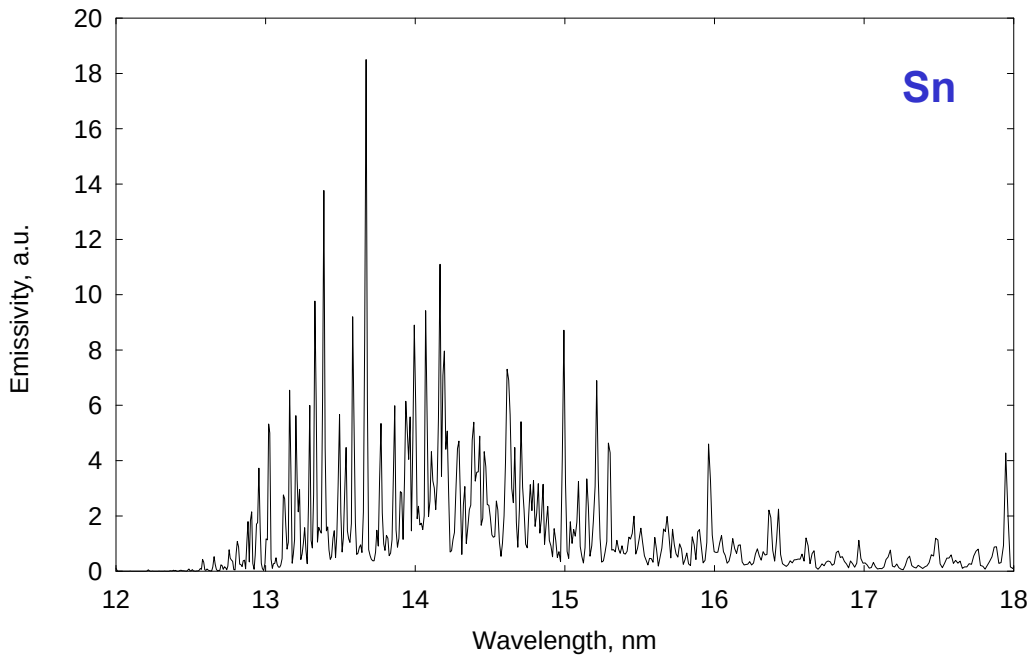
mathematical model: algorithms & schemes

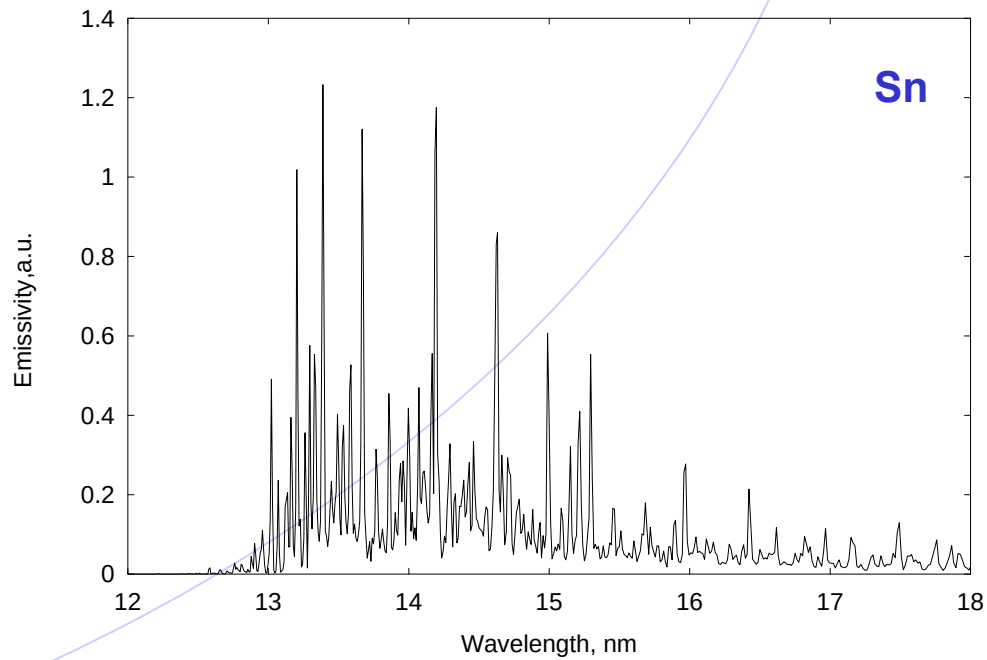


LTE & CRE

THERMOS & TERM calculations of emissivity of Sn in EUV

The average charge is the same Z=12





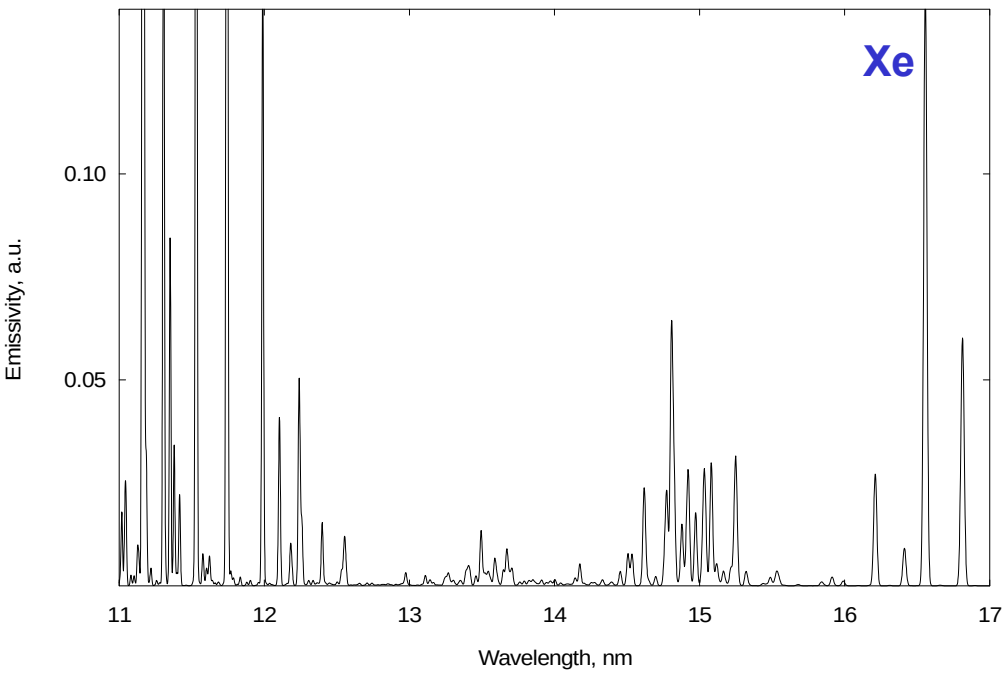
Optically thick plasma
LTE: T_e=16 eV

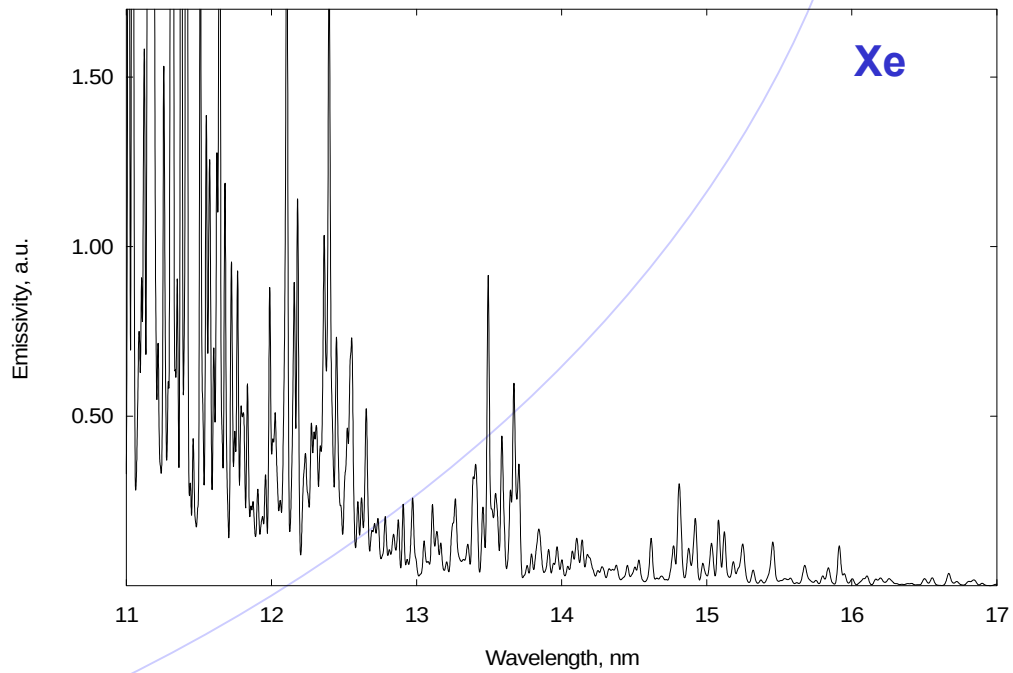
Optically thin plasma
CRE: T_e=40 eV

Equilibrium & Non- Equilibrium

THERMOS & TERM calculations of Xe EUV spectra

Detailed term accounting in intermediate coupling scheme approximation

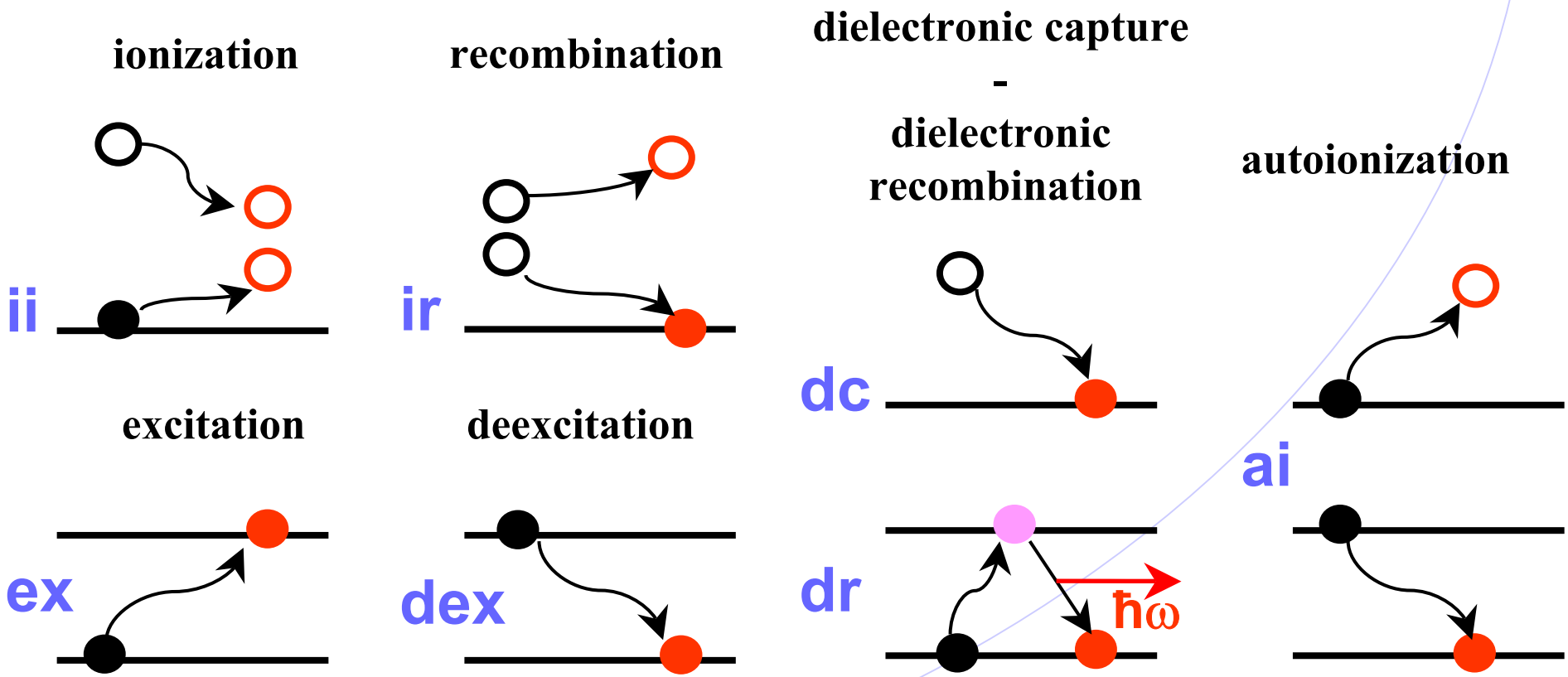




Corona equilibrium calculation of ionization & excitation rates

Non-equilibrium calculation with 0.4% reabsorption in lines

Electron - Ion Inelastic Impact Processes

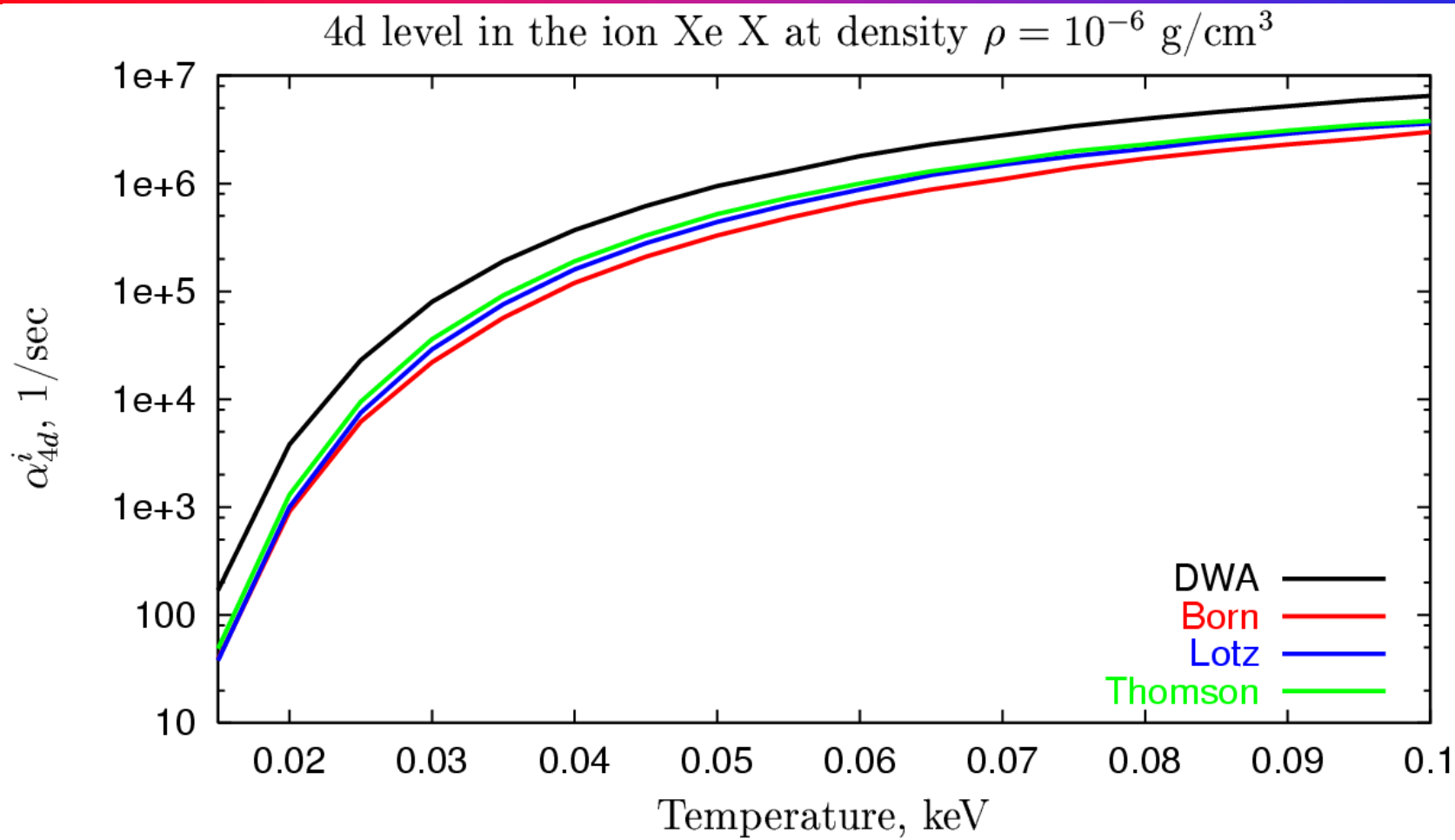


multicharged ion

(Xe^{+1},... Xe^{+9}, Xe^{+10}, Xe^{+11},...)

Non-Stationary Plasma

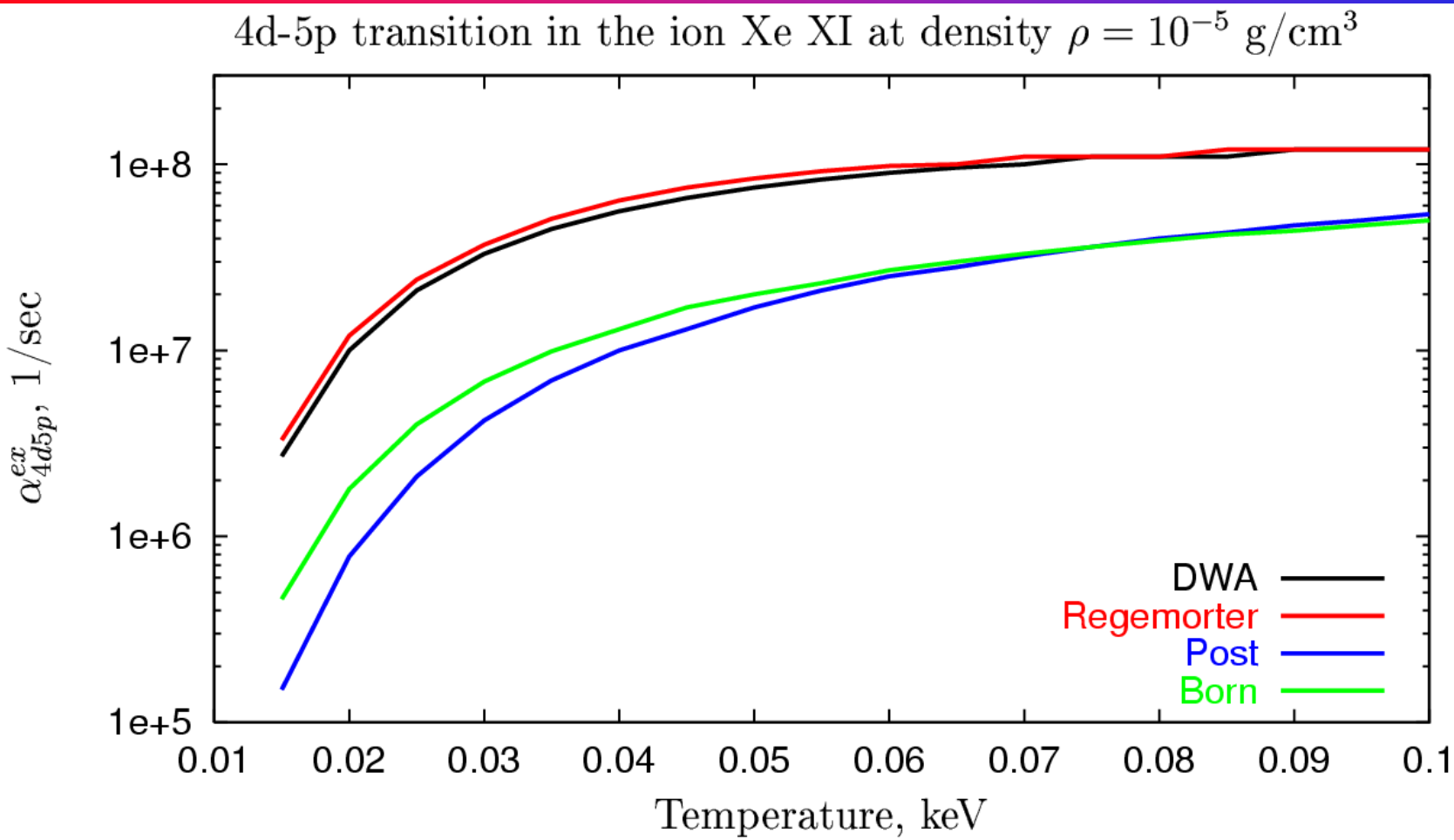
rates of impact ionization



Distorted-Wave Approximation (DWA), Born Approximation (Born), Lotz's formula (Lotz) and Thomson's formula (Thomson).

Non-Stationary Plasma

rates of impact excitation



Distorted-Wave Approximation (DWA), Van Regemorter's formula (Regemorter), Post's formula (Post) and Born Approximation (Born).

Z* for EUV source optimization

Simple changes in discharge parameters can make strong influences on

- **Plasma and radiation characteristics**
- **In-band radiation energy efficiency**
- **Electrode erosion and lifetime**

Z* Optimization of Capillary Discharge

typical modeling parameters

Power source

Charge energy	50 - 200 mJ
Current	5 - 20 kA
Pulse	6 ns

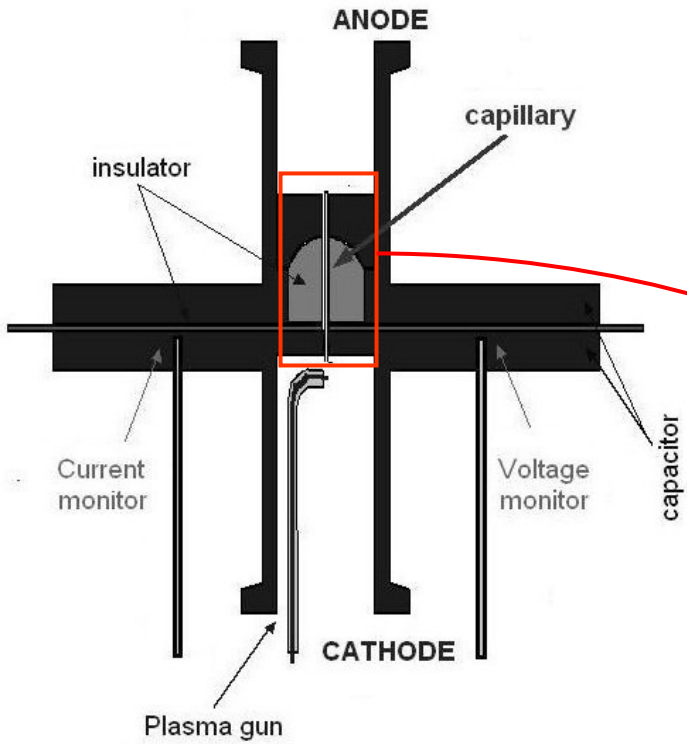
Capillary dimension: ∅ 0.8-3.2 mm, L = 6-12 mm

Various positions of the capillary

Gas: 0.1-1mbar, Xe + He admixtures
Kr + He admixtures
Ar + He admixtures

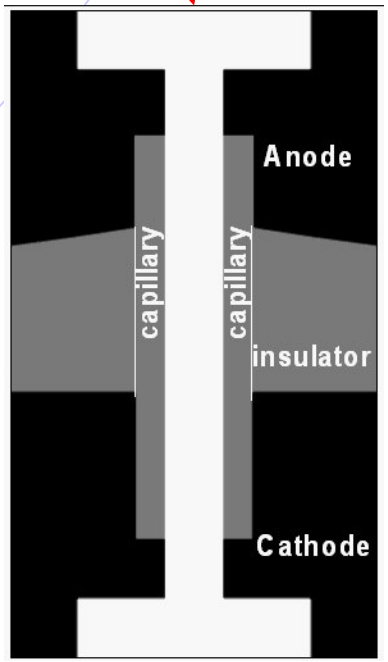
CD radiation source features

In-band EUV emission ~ 0.1mJ



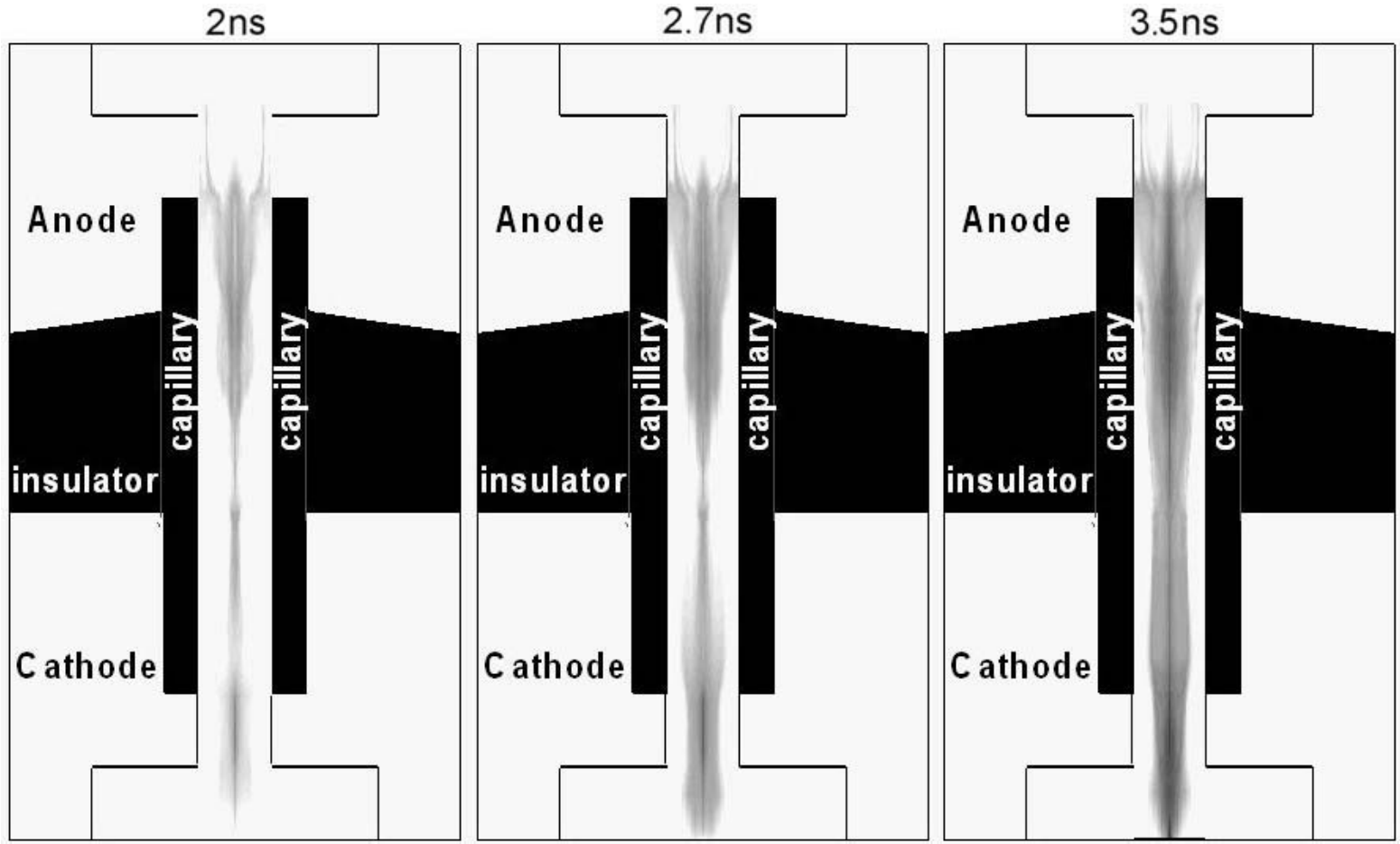
Experimental set up

Example of simulated geometry



Z* EEMHD Simulation

hollow cathode preionization

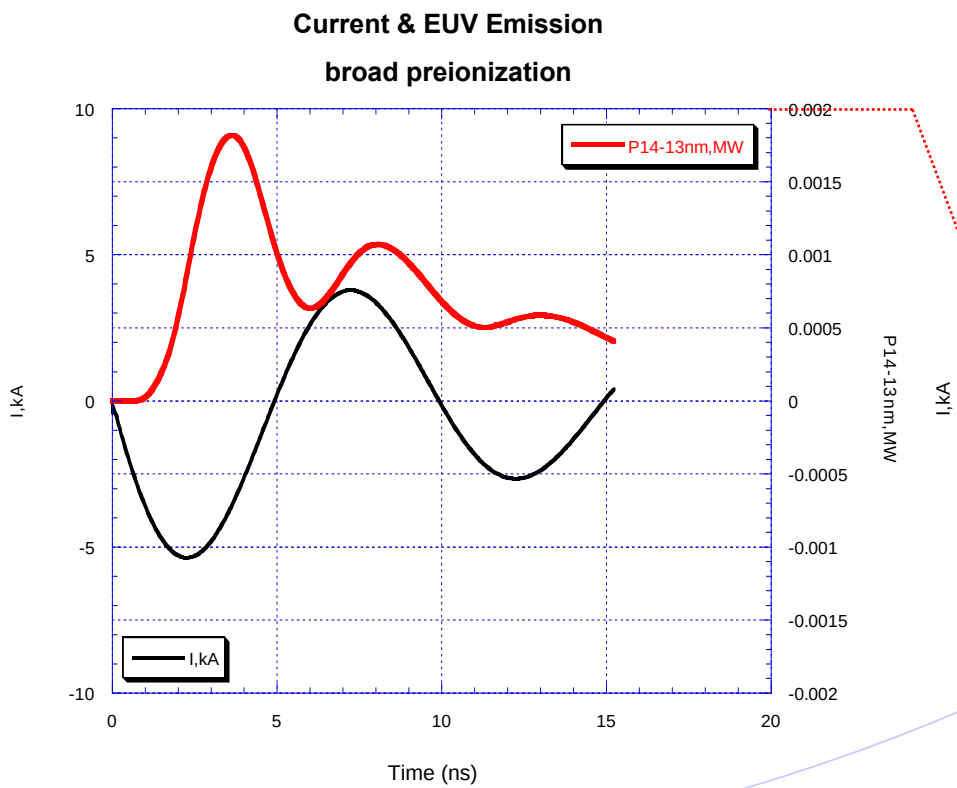


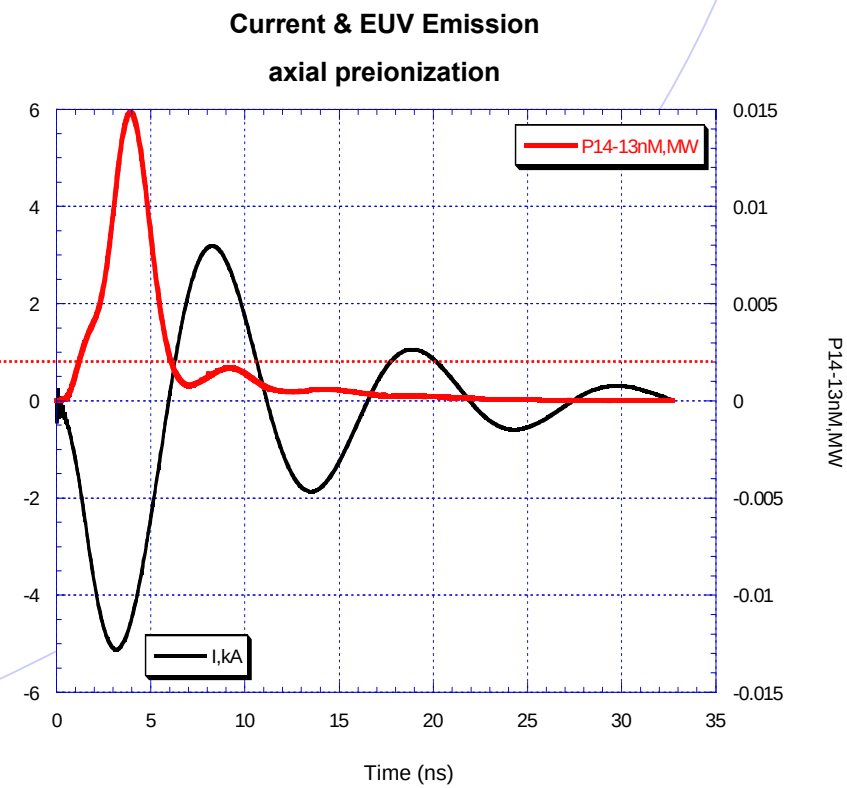
Ion density n_i dynamics in the capillary

Z* Simulation

effect of preionization

He:Xe mixtures



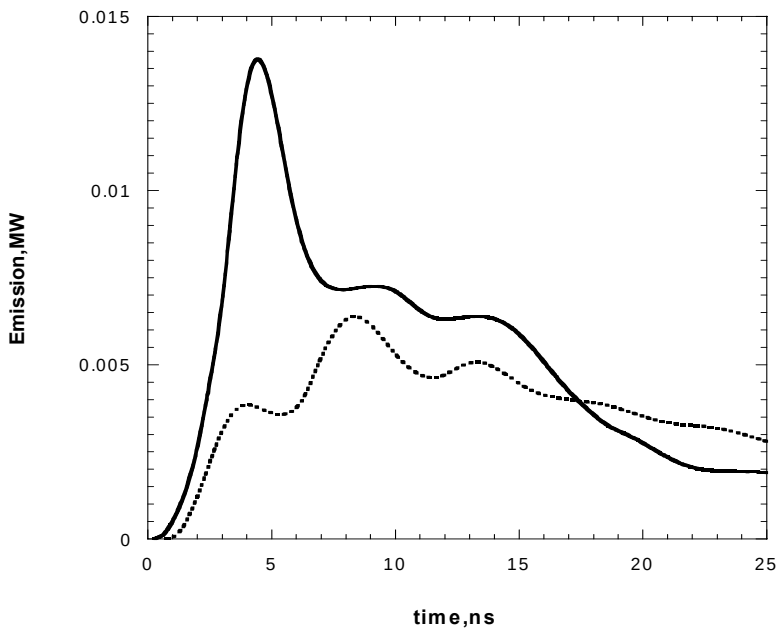


Xe 107 mtorr - 1.7 mtorr

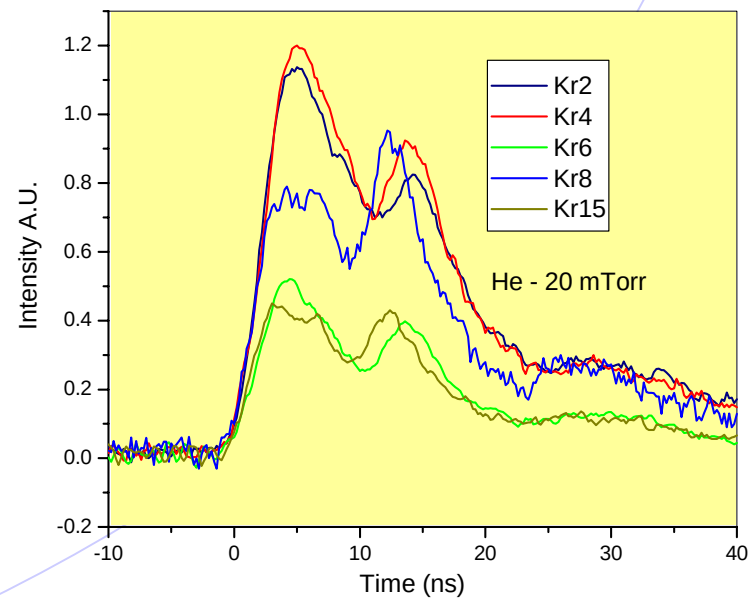
Z* Simulation vs. Experiment

effect of preionization

He:Kr mixtures



spectrum integrated with Zr filter transmission function

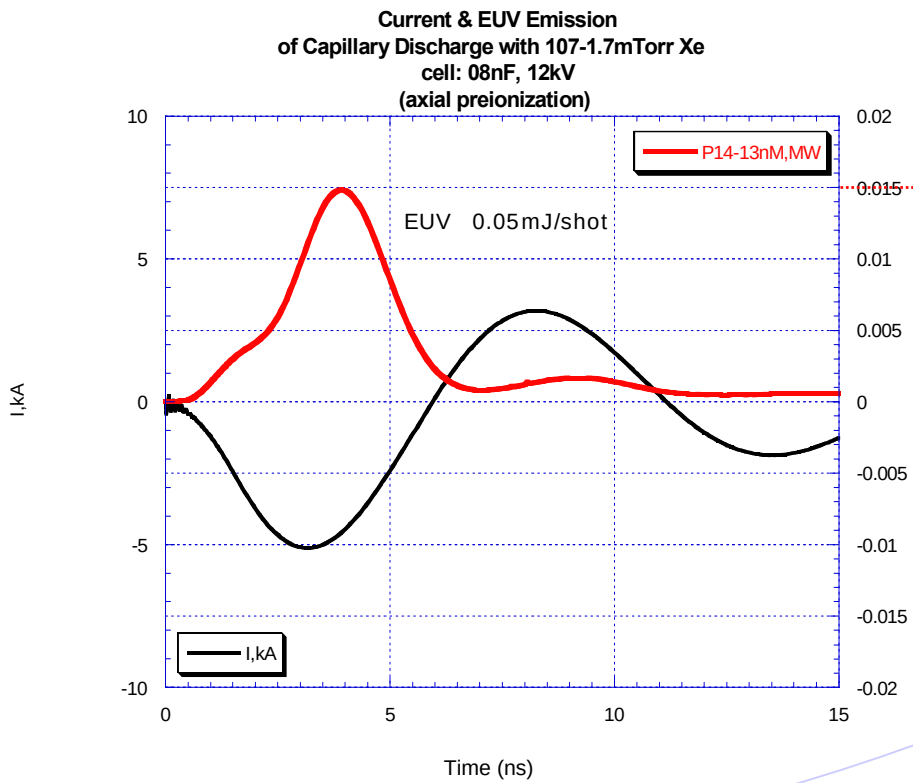


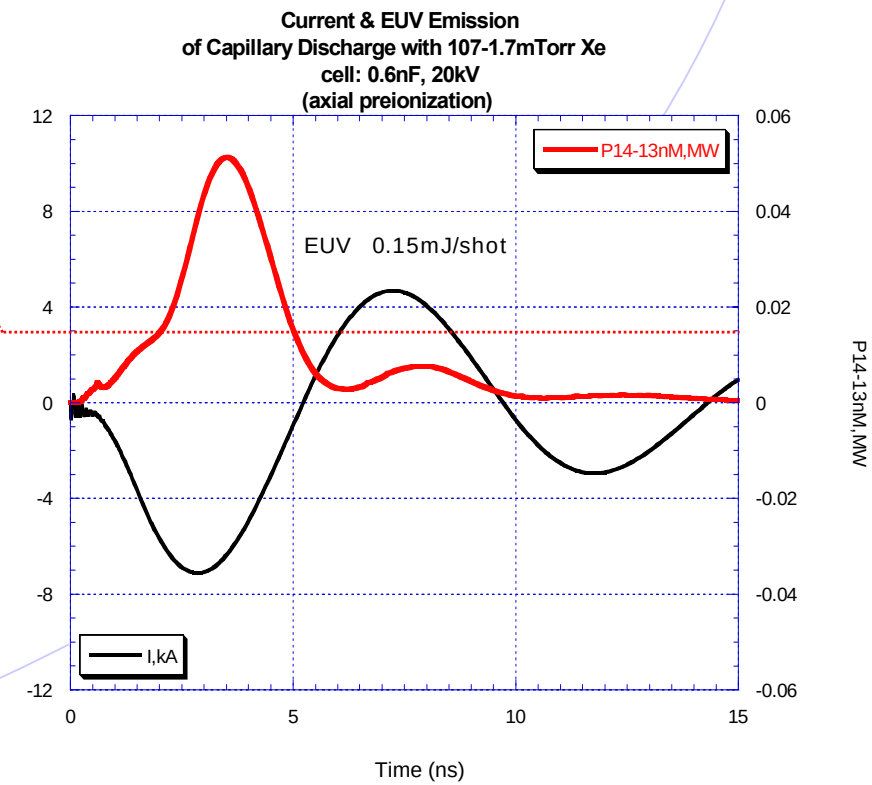
Zr filter

Z* Simulation

effect of energy input rate

He:10%Xe mixtures



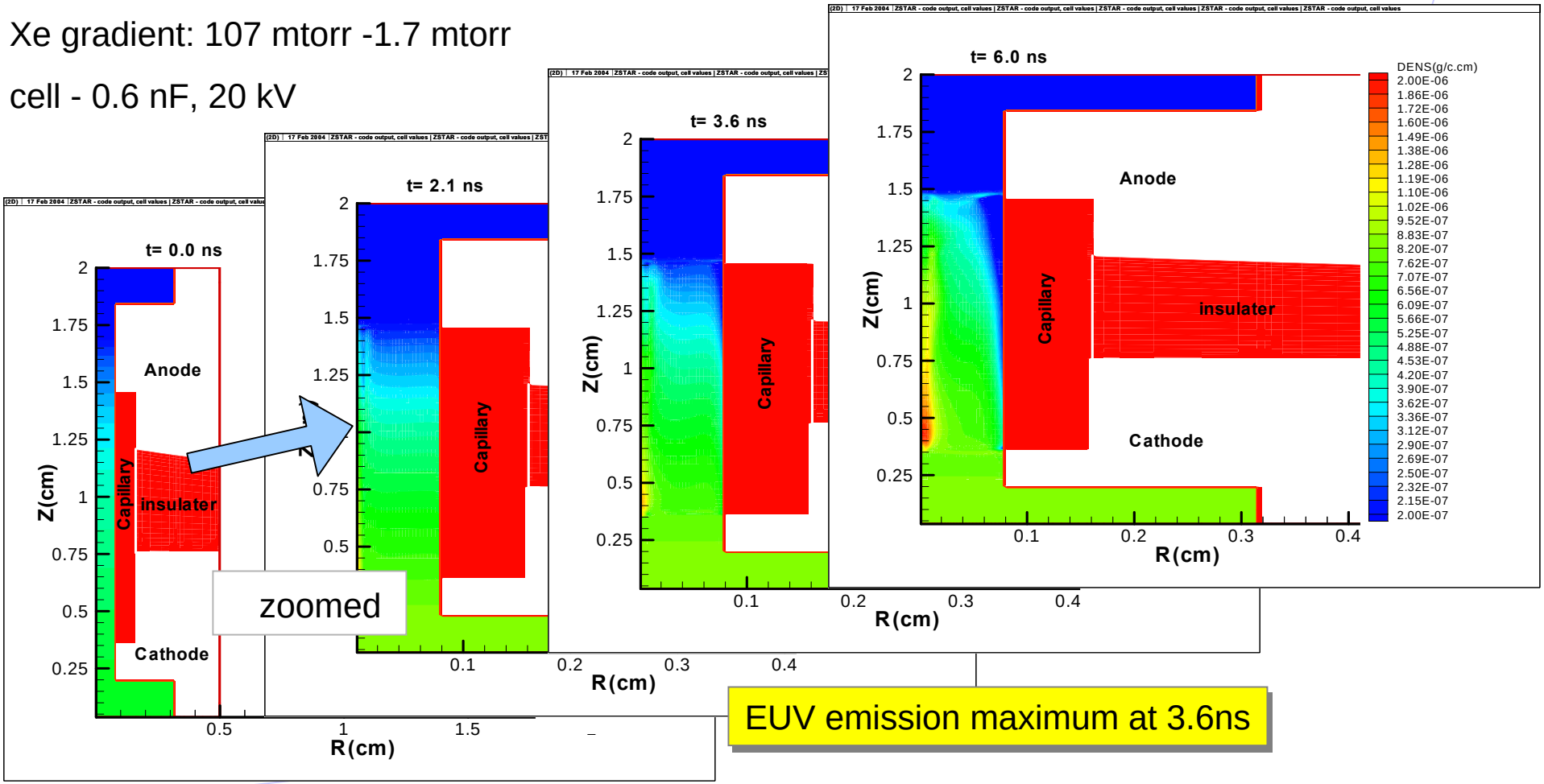


Capillary Discharge Density Dynamics

∅ 1.6mm capillary, 20kV charge

Xe gradient: 107 mtorr -1.7 mtorr

cell - 0.6 nF, 20 kV



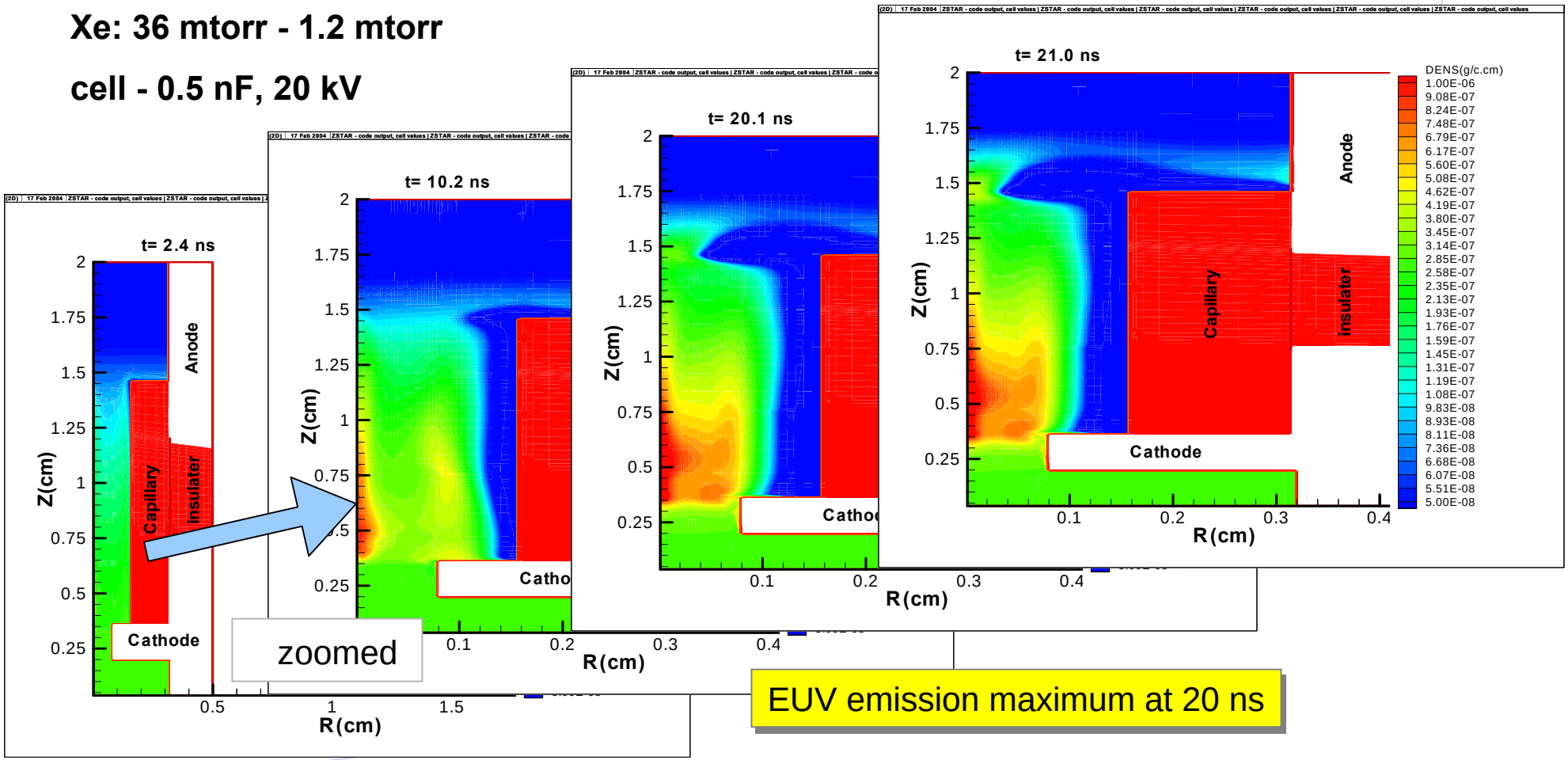
EUV emission maximum at 3.6ns

Discharge Density Dynamics

pinching anode plasma

Xe: 36 mtorr - 1.2 mtorr

cell - 0.5 nF, 20 kV



zoomed

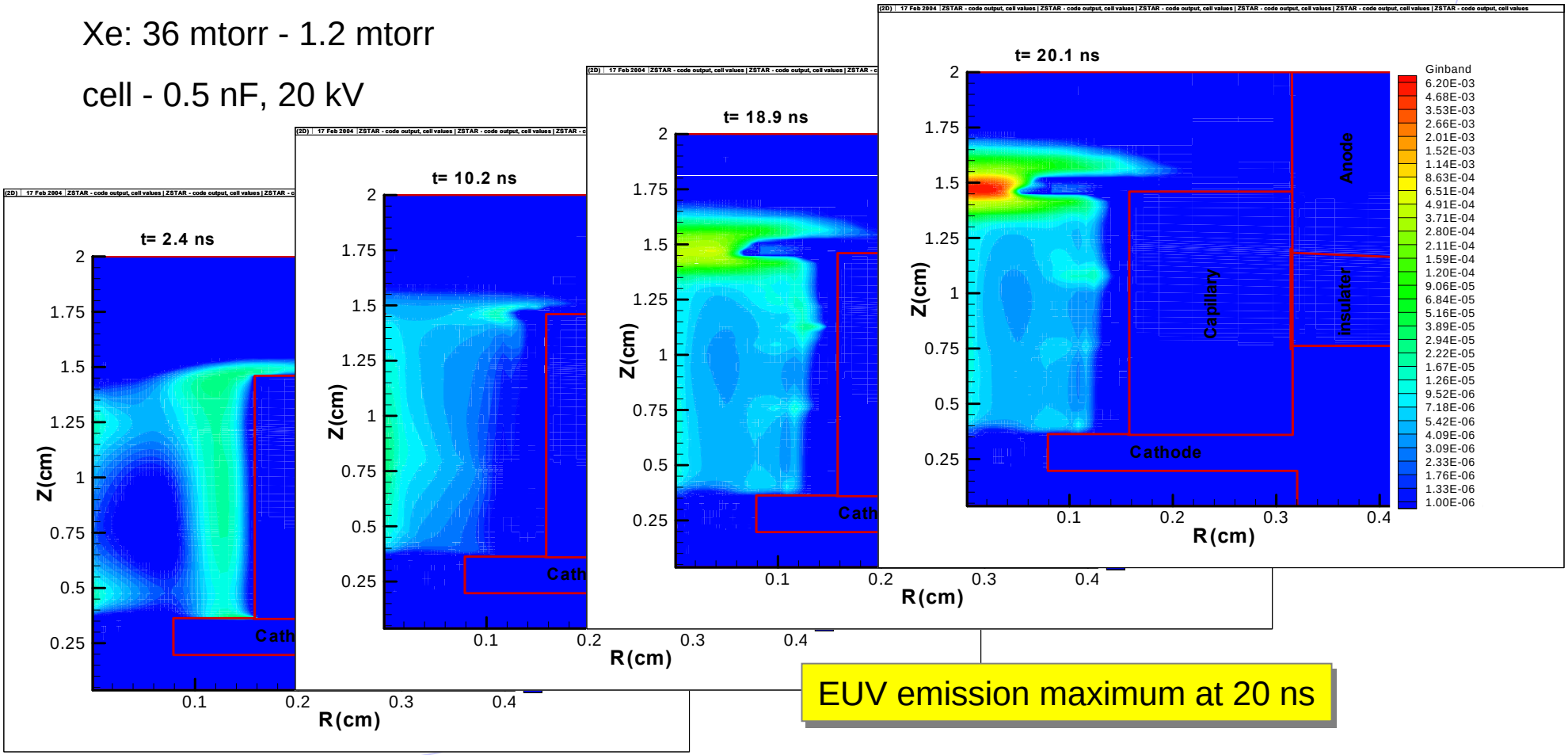
EUV emission maximum at 20 ns

EUV Radiation Source Dynamics

pinching anode plasma

Xe: 36 mtorr - 1.2 mtorr

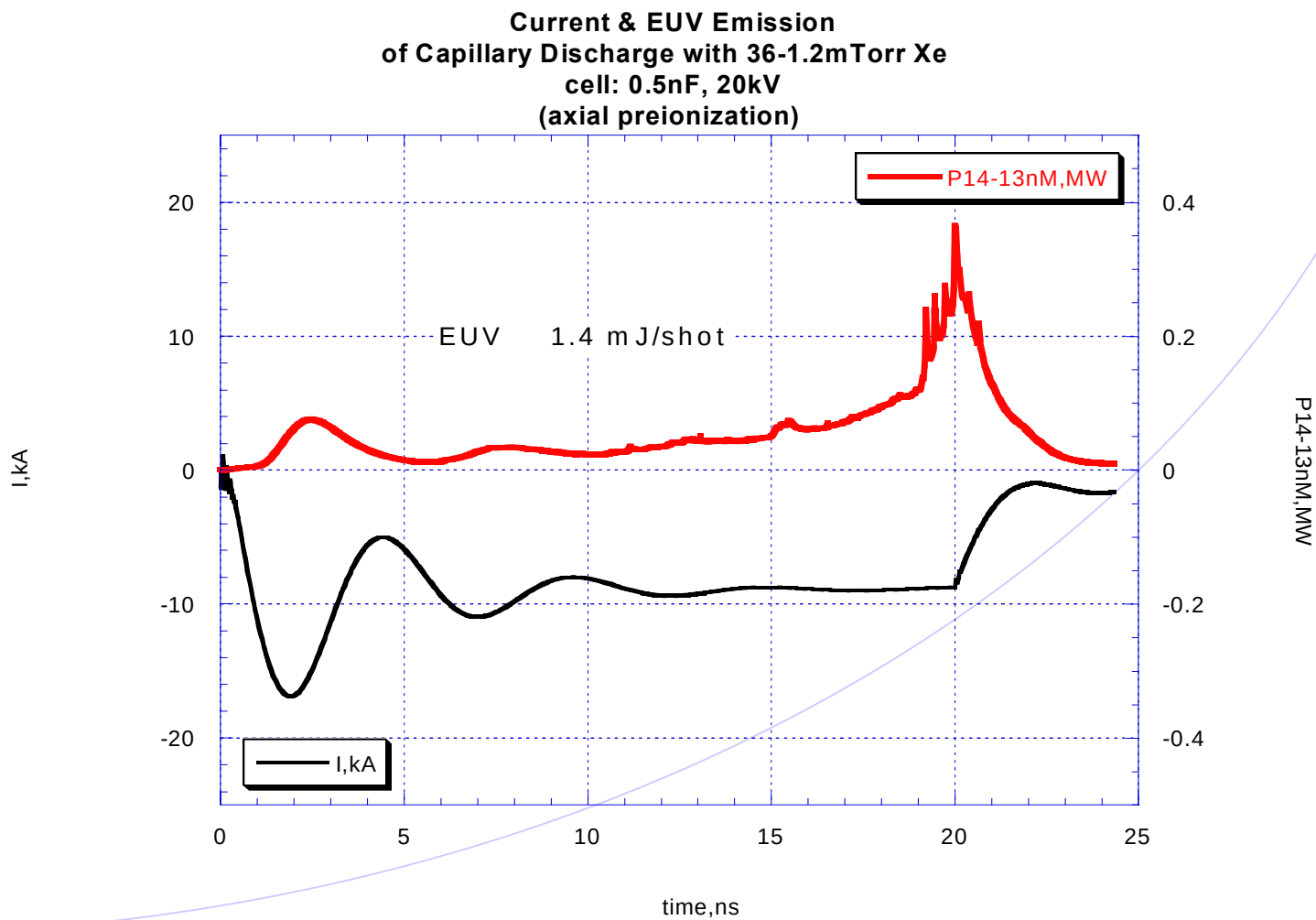
cell - 0.5 nF, 20 kV



EUV emission maximum at 20 ns

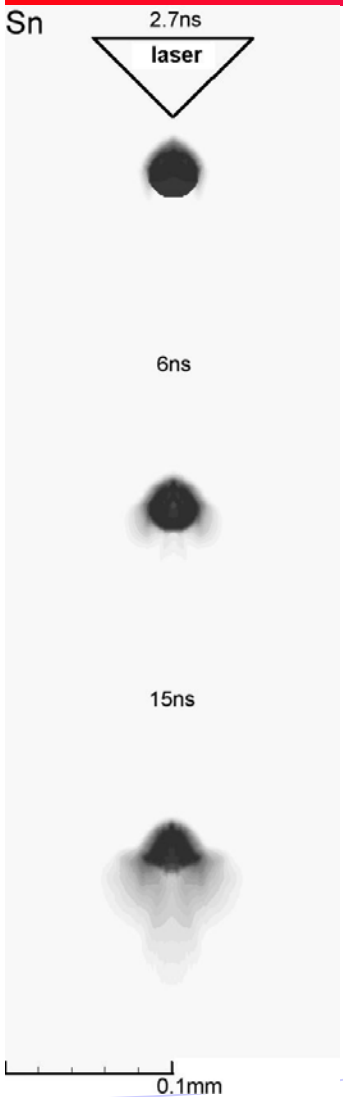
Z* Simulation

effect of pinching plasma



LPP Density Dynamics

solid tin and cryogenic xenon spherical droplets



Parameters:

- glass laser (1064nm)
- flat pulse 15ns
- laser energy 0.05J
- focal spot with 40μm diameter

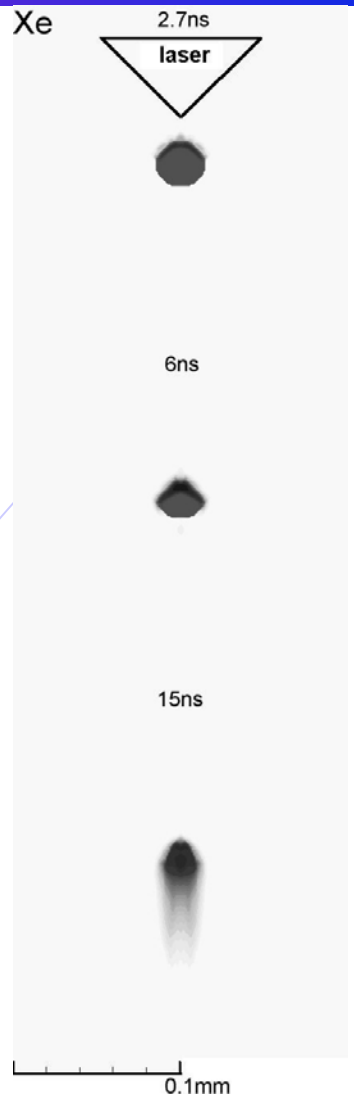
Targets: 30μm diameter solid tin or cryogenic xenon droplets

Features:

- laser absorption and EUV emission are localized at critical density
- interaction of the laser light with plasma at critical density is unstable,
- the emitting shell consists of hot spots

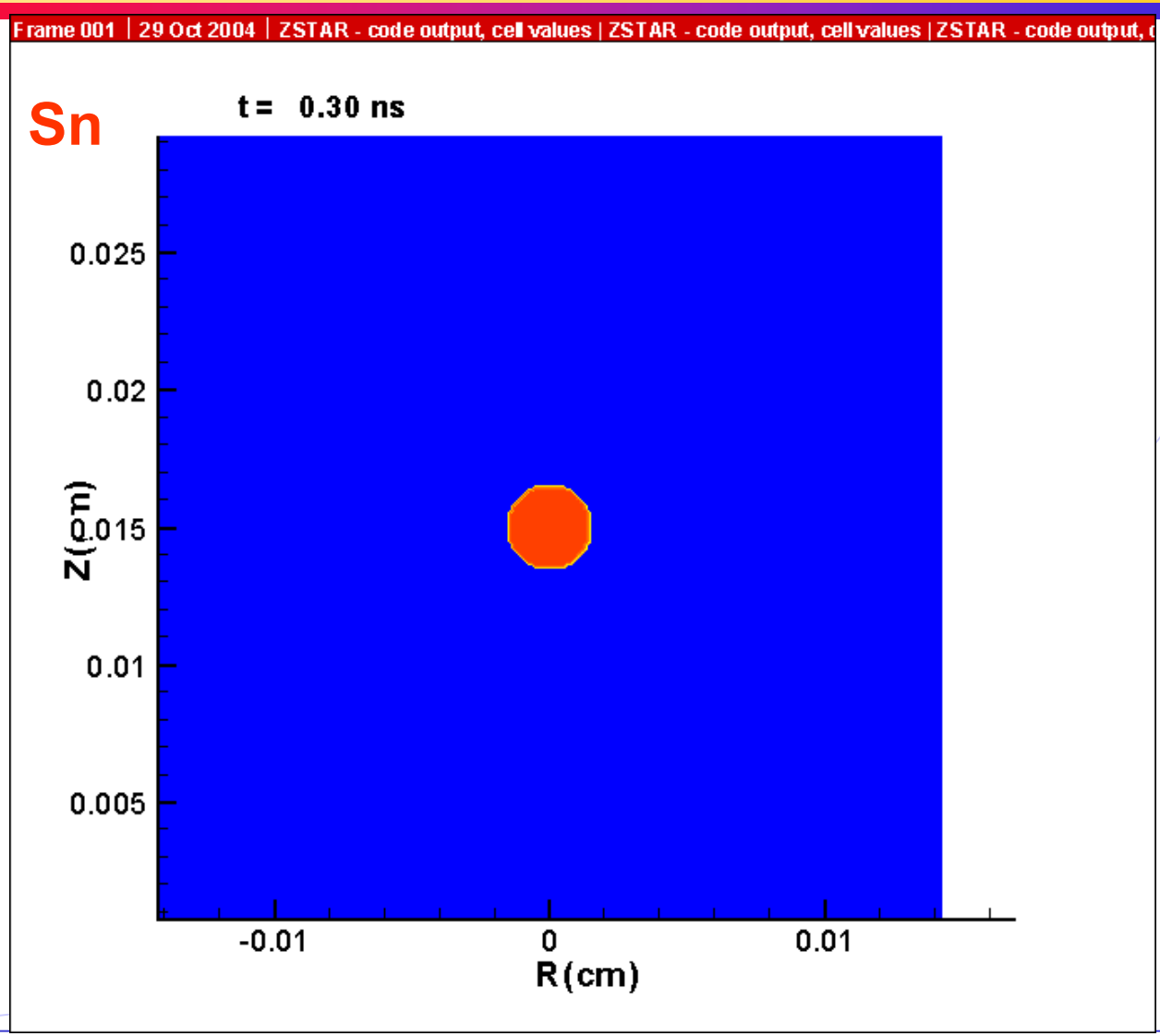
Differences:

- tin target has absorbed 48mJ
- xenon target has absorbed 34mJ



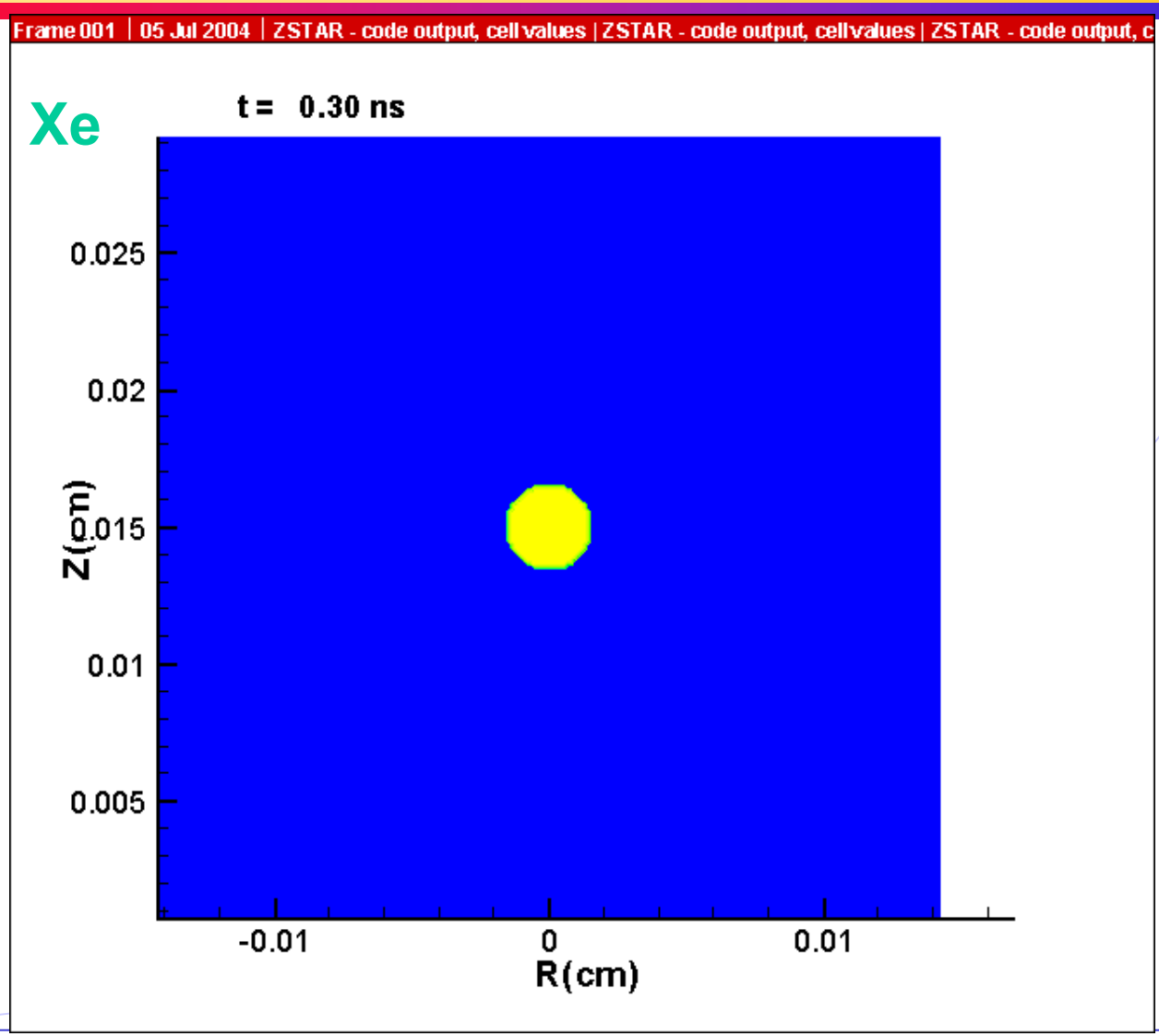
LPP Density Dynamics

solid tin spherical droplet



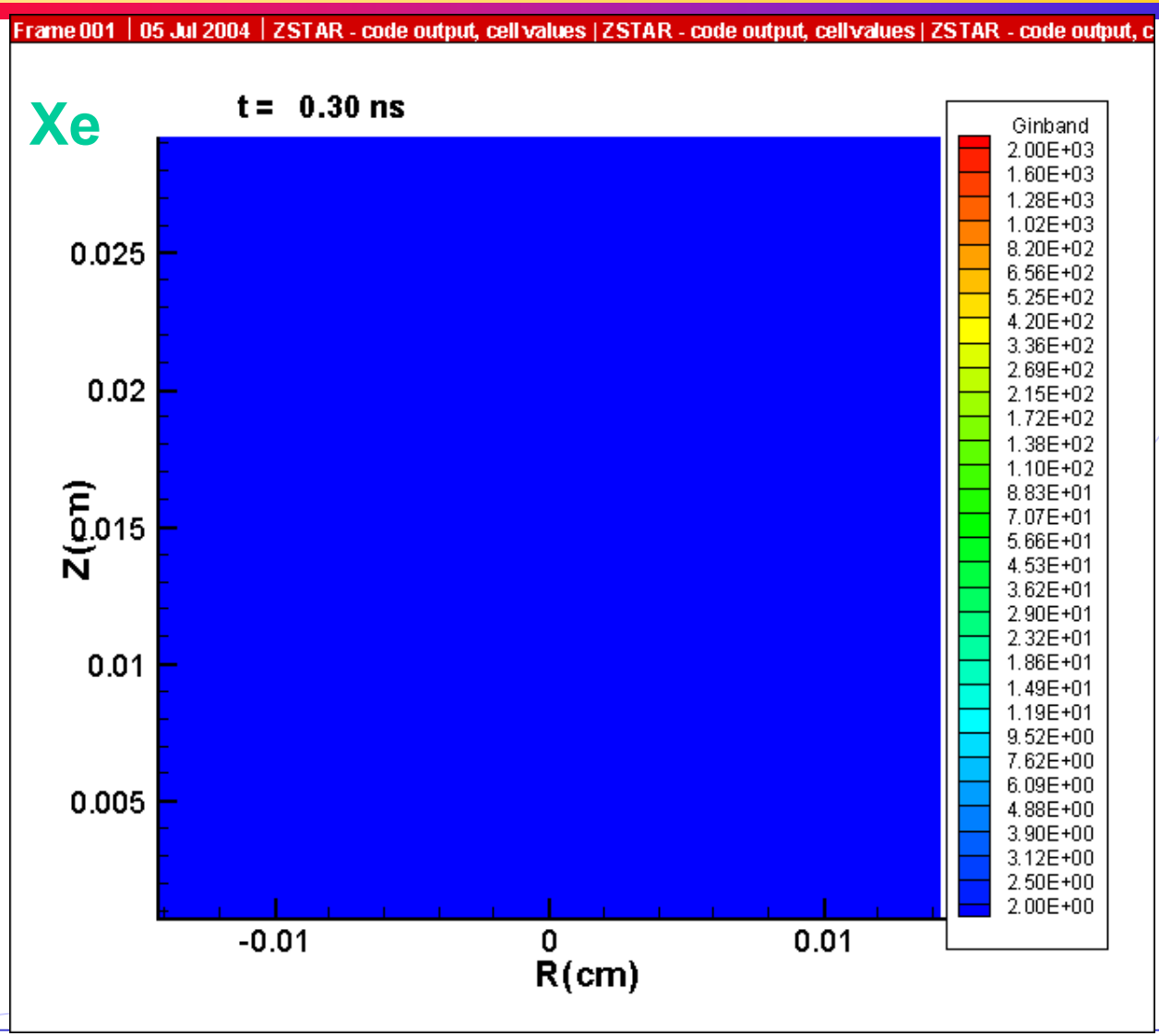
LPP Density Dynamics

cryogenic xenon spherical droplets



LPP EUV Emitter Dynamics

cryogenic xenon spherical droplets

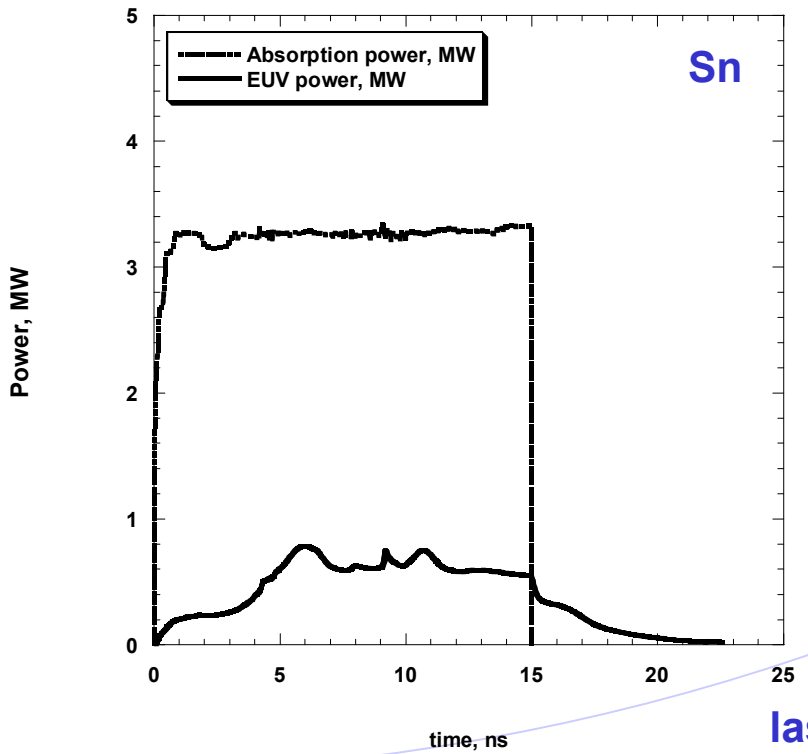


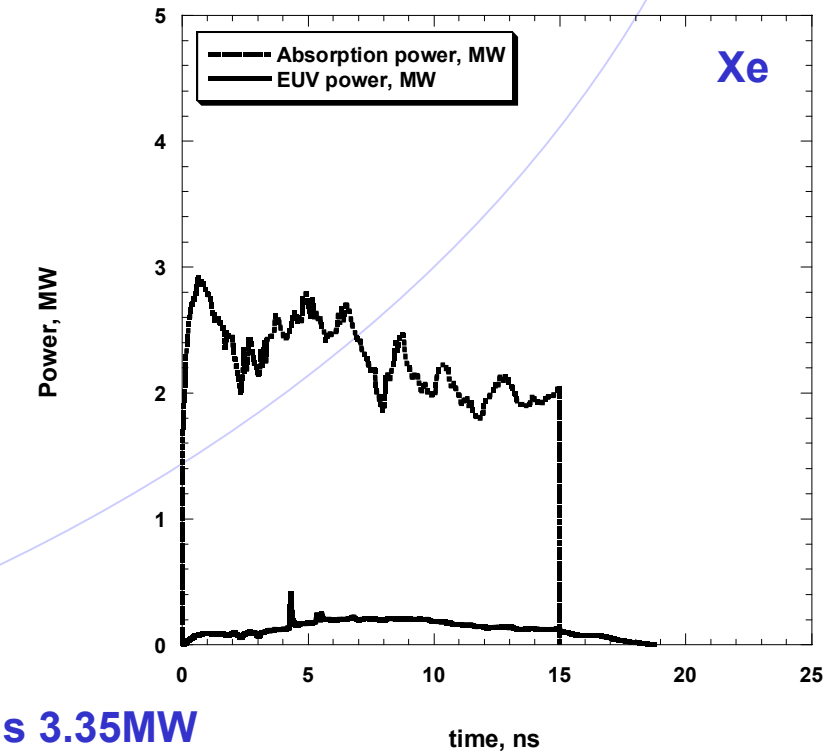
Z* Optimization

LPP emission efficiency (spherical droplets)

EUV yield in 2% bandwidth

- from Sn target: 2.46mJ, i.e., 1.48mJ/2π, CE~3%
- from Xe target : 0.32mJ/2π, CE~0.65%





laser power is 3.35MW

Z* Black Box Modeling Engine

for EUV plasma sources

A Blackbox Modelling Engine (BME), is an instrument based on the adaptation of the RMHD code Z*, integrated into a specific computation environment to provide a turn key simulation instrument.

BME is equiped with special features to enable routine plasma modelling without specialist knowledge in numerical computation.

Two different operating modes are provided;

a) Detailed Physics mode & b) Fast Numerics mode.

In the Detailed Physics mode, non-stationary, non-equilibrium radiation physics have been introduced to allow the modelling of transient plasmas in DPP and LPP.

In the Fast Numerics mode, the system architecture and the radiation transport is simplified (a computation time is 100 – 1000 times shorter than in the Detailed Physics mode).

The Fast Numerics mode allows the BME to be used realistically in parametric scanning to explore complex physical set up, before using the Detailed Physics mode to generate data for comparison with experimental measurements.