A Black-box Modeling Engine
for Optimization Modeling of EUV Plasma Sources

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Blackbox Modeling Engine (BME) is a numerical tool based on the adaptation of the radiative magnetohydrodynamic (RMHD) code Z*, integrated into a specific computation environment to provide a turnkey simulation instrument. It is developed in EPPRA to specifically address certain key issues in EUV plasma sources. BME is equipped with special features to enable routine plasma modeling without specialist knowledge in numerical computation. Two different operating modes are provided in BME; a) Detailed Physics and b) Fast Numerics mode. In the Detailed Physics mode, non-stationary, non-equilibrium radiation physics have been introduced to allow the modeling of transient plasmas in DPP and LPP. In the Fast Numerics mode, the system architecture and the radiation transport is simplified. This results in a computation time much shorter than in the Detailed Physics mode. This feature 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. The code was applied to study the plasma dynamics in the micro plasma pulsed (MPP) discharge at EPPRA with transient ionization processes. The simulations have permitted to understand critical issues in discharge, to choose power supply parameters and to improve efficiency and lifetime of MPP source. The code was also applied to study LPP from solid tin and cryogenic xenon droplets illuminated by single or double pulse 10 – 200mJ energy laser either glass laser or combined with CO₂ laser. Double pulse permits to prepare an optimal plasma distribution during pre-pulse and necessary plasma parameters during main pulse for efficient EUV emission.
Code ZETA for plasma modelling in HEDP

  - TRINITI (group leaders S.V. Zakharov, A.E. Stepanov):
    - plasma physics, RMHD, radiation transport & spectra
  - KIAM (group leader V.G. Novikov): atomic physics, tables for EOS & spectra

Simulations:
- 1996-1998: Z-pinch experiments at Angara (TRINITI), Z-machine (SNL)
- 1999-2000: with EPPRA:
  - POS (Ecole Polytechnique): Capillary discharges (Bochum, EPPRA)

Code Z* for modelling of experimental and industrial plasmas
- 2001-2005: at EPPRA, simulations of a set of configurations for experimental plasma & EUV sources:
  - DPP: HCTZP (Philips, Xtreme); DPF (Cymer); Capillary discharge (EPPRA)
  - LPP: xenon jet (FOM); cryogenic xenon (Xtreme) & solid tin targets
Non-Equilibrium plasma

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
Non-stationary ionization
impact ionization cross-sections in DWA

Distorted-Wave Approximation (DWA), Born Approximation (Born), Thomson’s formula (Thomson) and experimental data (Experiment).

(for details see the poster 43 by Vasily ZAKHAROV et al.)
mathematical model: algorithms & schemes

Numerical diffusion!

Adaptive grid

Small time step!

(zero for plasma in magnetic field)

Euler variables

Explicit scheme is stable conditionally

Lagrangian-Euler variables

Completelly conservative, implicit scheme

RMHD

Lagrange variables

Non-conservative scheme

Grid crossing!

Adaptive grid

No energy balance!
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 equipped 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.
Z* BME

on-line monitor interface
Simple changes in discharge parameters can make strong influences on

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

**Optimization of capillary discharge**

**typical modeling parameters**

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**Power source**
- Charge energy: 0.1 – 0.4 J
- Current: 5 - 10 kA
- Pulse: ~10 ns

**Capillary dimension:**
- Ø 0.8-1.6 mm
- L = 6-12 mm

**Various positions of the capillary**

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

**Capillary discharge emission features:**
- Plasma channelling and focusing of EUV radiation
- Collectable EUV emission @ 13.5nm 2% band: 0.25 - 0.5%
Z* BME  
Optimization of capillary discharge power parameter scanning (at the same charge energy 0.25J)

4th International EUVL Symposium  
7-9 November, 2005, San Diego, USA
Z* BME

Heat loading on electrodes
geometry parameter scanning

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LPP density dynamics

solid tin and cryogenic xenon spherical droplets

Parameters:
- glass laser (1064nm)
- flat pulse 15ns
- laser energy 0.05J
- focal spot with 40\(\mu\)m diameter

Targets: 30\(\mu\)m 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 simulations
emission efficiency (spherical droplets)

EUV yield @ 2% bandwidth

• solid tin target: CE~3% in 2p

• cryogenic xenon target: CE~0.65%

Example with laser energy 50mJ
Features for CO₂ laser:
- lower critical density $n_{\text{critical CO}_2} \approx 0.01 \, n_{\text{critical Nd}}$
- higher diffraction
- Nd-laser pre-pulse is used to prepare plasma
- for CO₂ laser plasma volume should be larger, lower target mass

Target: cryogenic Xe droplet
~20µm diameter

- lower reabsorption of EUV
- for high CE, the laser energy should suitable
  400mJ $\rightarrow$ CE~0.45% into $2\pi$
  200mJ $\rightarrow$ CE~1% into $2\pi$

Pre-pulse:
- Nd-glass laser (1.064µm)
- laser energy 2-10mJ
- Gaussian profile 80ps FWHM
- focal spot diameter ~20µm

Main pulse:
- CO₂-gas laser (10.6µm)
- laser energy 200-400mJ
- Gaussian profile 5-10ns FWHM
- focal spot diameter ~200µm

Time delay 50-70ns
Z* BME

LPP dynamics
Nd-glass & CO$_2$ double pulse

Plasma density dynamics

at the end of pre-pulse

at the peak of EUV emission

start of main-pulse

EUV source

In-band EUV emissivity

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