Progressing Modeling of LPP, Laser Induced DPP and Hollow Cathode Micro Plasma Pulsed EUV Sources with Z* Blackbox Modeling Engine

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Abstract

Z* Blackbox Modeling Engine (Z*BME) is a numerical tool based on the adaptation of the 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. Non-stationary, non-equilibrium radiation physics have been introduced into the code, to allow the modeling of transient plasmas in DPP and LPP. The Z*BME is used realistically in parametric scanning to explore complex physical set up and to generate data for comparison with experimental measurements. The code was applied to benchmark the plasma dynamics and EUV emission features of tin in the LPP and laser triggered DPP EUV sources. The Z* BME was used in parametric scanning of micro plasma pulsed (MPP) discharge at EPPRA with transient ionization processes under influence of electron beam from hollow cathode, non-equilibrium radiation transport, EUV emission, electrode heat loading and debris production to choose power supply parameters and to improve efficiency and lifetime of MPP EUV source with non-destructive radiation collimating-focusing structure.
Source, experience & benchmarks

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

- 2001-2006: at EPPRA, simulations experimental plasma & EUV sources :
  **DPP**: HCTZP (**Philips**); DPF (**Cymer**); Capillary discharge (**EPPRA**)
  Z-Pinch (**Xtreme**); laser triggered discharge
  **LPP**: xenon jet (**FOM**); cryogenic xenon (**Xtreme**); liquid tin
  & solid tin targets
mathematical model: algorithms & schemes

- Numerical diffusion!
- Adaptive grid
- Detailed grid
- Small time step! (→ zero for plasma in magnetic field)
- Euler variables
- Explicit scheme is stable conditionally
- Lagrange-Euler variables
- Completely conservative, implicit scheme
- RMHD
- Lagrange variables
- Non-conservative scheme
- Grid crossing!
- Adaptive grid
- No energy balance!
Non-stationary ionization

impact ionization cross-sections in DWA

Distorted-Wave Approximation (DWA), Born Approximation (Born), Thomson’s formula (Thomson) and experimental data (Experiment).
A Z* Blackbox Modelling Engine (Z* BME), is an instrument based on the adaptation of the 2D RMHD code Z*, integrated into a specific computation environment to provide a turn key simulation instrument.

Z* 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 2D geometry. Detailed Physics mode has extensions for spectral transfer and thermal analysis post-processing.

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
2-D Benchmarking of LPP source

tin plane target

![Schematic of experiment]

**Laser pulse**

1064nm (1 beam/normal incidence)

Lens focus 400 mm; Beam Ø10mm

Pulse duration (Gaussian) HWHM & Spot size Ø

2.2 ns 8ns

660μm(< 2×10^{11}W/cm²) 480 μm(< 2×10^{11}W/cm²)

270μm(> 2×10^{11}W/cm²) 270 μm(> 2×10^{11}W/cm²)
Z*BME

2-D LPP Dynamics & Evolution of EUV Emission Spectra

2.2ns
10^{11}\text{W/cm}^2

T_e = 35-40\text{eV}
N_e = 2 \cdot 4 \cdot 10^{20} \text{ cm}^{-3}

8\text{ns}
10^{11} \text{W/cm}^2

T_e = 30-38\text{eV}
N_e = 3 - 5 \cdot 10^{20} \text{ cm}^{-3}
**Z*BME**

**Benchmarking of Laser Triggered DPP**

**liquid tin at tungsten cathode**

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**Experimental geometry**

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**Simulated geometry**

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**Calculated**

Current & EUV Emission of Laser Triggered DPP of ISAN

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**Discharge parameters**

- **Anode**: material Mo
- **Cathode**: W with melted tin at 300 °C
- **L**: 11 nH; **C**: 0.413 μF; **V**: 4.6kV

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**Laser pulse**

**Energy**: 40 mJ

**Pulse duration (Gaussian)**

**HWHM**: 23 ns

**Focus spot**: Ø 0.3 mm

**Lens focus**: 400 mm

**Beam**: Ø 6mm

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**CE** = \[ \frac{\text{emission} @ 2\% \text{ band} \times 4\pi}{2 \times \text{capacitor charge}} \] = 1-1.2%
**Z*BME**

**2-D DPP Dynamics**

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**Plasma mass density at break down moment**

240ns

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**Plasma electron density at EUV emission peak**

318ns

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EUV Source Workshop

19 October, 2006, Barcelona, Spain
**EUV Emissivity & Emission Spectra**

EUV emitter at radiation maximum

Calculated multigroup

EUV Spectrum from Laser Triggered DPP of ISAN

\[ t = 3.1832 \times 10^2 \text{ ns} \]

\[ \text{Geuv(MW/ccm)} \]

\[ \begin{align*}
3.8 \times 10^4 & \\
3.6 \times 10^4 & \\
3.5 \times 10^4 & \\
3.3 \times 10^4 & \\
3.1 \times 10^4 & \\
3.0 \times 10^4 & \\
2.8 \times 10^4 & \\
2.6 \times 10^4 & \\
2.5 \times 10^4 & \\
2.3 \times 10^4 & \\
2.2 \times 10^4 & \\
2.0 \times 10^4 & \\
1.8 \times 10^4 & \\
1.7 \times 10^4 & \\
1.5 \times 10^4 & \\
1.3 \times 10^4 & \\
1.2 \times 10^4 & \\
1.0 \times 10^4 & \\
8.4 \times 10^3 & \\
6.8 \times 10^3 & \\
5.1 \times 10^3 & \\
3.5 \times 10^3 & \\
1.8 \times 10^3 & \\
2.0 \times 10^2 &
\end{align*} \]

\[ \text{Qv(MW/eV/srad)} \]

\[ \begin{align*}
2.5 & \\
2 & \\
1.5 & \\
1 & \\
0.5 & \\
0 &
\end{align*} \]

\[ \begin{align*}
10 & 12 & 14 & 16 & 18 & 20 & \text{nm}
\end{align*} \]

\[ T_e = 50-100 \text{eV}; \quad N_e = 5-8 \times 10^{17} \text{cm}^{-3} \]

\[ Z = 11-14 \]

\[ T_i \gg T_e; \quad \text{non-stationary non-LTE plasma} \]
Heuristics Model for CE Estimation
(doubling of losses)

\[
CE = \frac{\text{emission @ 2\% band to } 4\pi}{2 \times \text{capacitor charge}}
\]

Maximal emissivity from

\[
\frac{\text{transparent plasma @ 2\% band to } 4\pi}{\text{Total plasma emission}} = 32\% \quad \text{(for tin)}
\]

\[
\times \frac{1}{2} \times \left( \frac{\frac{2\pi}{4\pi}}{4\pi} \right)
\]

\[
\times \frac{1}{2} \quad \text{(heating – cooling)}
\]

\[
\times \frac{1}{2} \quad \text{(plasma energy to radiation)} = 4\% \quad \text{maximum for LPP}
\]

\[
\times \frac{1}{2} \quad \text{(charge energy to plasma energy)} = 2\% \quad \text{maximum for simple DPP}
\]

\[
\times \frac{1}{2} \quad \text{(reabsorption)}
\]


MPP Capillary Discharge EUV Source

typical parameters

Power source
- Charge energy: 0.1 – 0.4 J
- Current: 5 - 10 kA
- Pulse: ~10-20 ns

Capillary
- Dimension: L = 12-18 mm
- ∅ 1.6-3.2 mm

Various electrode geometries

Gas:
- 0.1-1mbar, Xe+He+Sn admixtures
- Kr + He; Ar + He admixtures (for technology development)

Capillary discharge emission features:
Plasma channelling and focusing of EUV radiation
Xe: Collectable EUV emission @ 13.5nm 2% band: ~0.01% of charge energy
Hollow Cathode Electron Beam

increasing of ionization degree in discharge plasma

- Various percentage of fast electrons
- Ionization equilibrium with fast electrons of various percentage in comparison with Maxwell distribution in Ar (0%).
- Energy of fast electrons $E = 5$ keV
- Relative concentration $\zeta = 0.1, 1, 10\%$.

Ionization equilibrium with fast electrons of various percentage in comparison with Maxwell distribution in Ar (0%).

![Graph](image-url)
• MPP radiation shows radiation guiding (first collimation) through plasma density structure inside capillary

• strong dependence on operating pressure gradient and energy input rate

• agreement with 3-D pinch compression demonstrated in Z*BME™ simulation
Z*BME

MPP Source
operation with He:Ar and He:Xe (charge energy 0.4J)

3D plasma compression

Factor ~ 7 for EUV emission
Plasma-electrode interaction mechanisms

- heating of the electrodes by joule dissipation at electrode-plasma transition;

  \[
  \sigma(T) \sim \sigma_0 \frac{\theta}{T} \quad \text{thermal instability:} \quad c_v \frac{\partial T}{\partial t} = \frac{j^2}{\sigma}
  \]

  \[
  T = T_0 \exp\left[\int \gamma \, dt\right]
  \]

  \[
  \gamma = \frac{j^2}{\sigma_0 \theta c_v}
  \]

- surface heating & plasma cooling by means of plasma thermal conduction;

- surface heating and damage by plasma radiation;

- optical elements damage by fast ions & atoms emitted from the plasma (ambipolar and E-field acceleration, shocks, Maxwell tails etc).
Low energy unit provides

- Low heat loading on electrodes and insulators
- Long lifetime
- Low debris production

EUV Source Workshop
19 October, 2006, Barcelona, Spain
Ablation of electrodes is induced by x-ray plasma radiation & joule heating, and partially by thermal conduction from plasma.
Summary

Achievements

• Z* has clearly demonstrated maturity, in terms of comprehensive physics and optimized numerics, in modelling of complex radiating EUV plasmas

• Z*BME is the only 2-D radiation MHD code available today, on commercial terms for EUV source modelling and optimization.

Activity

• Benchmarking exercise for LPP and DPP with other 2-D EUV plasma modelling codes

• Benchmarking with experimental results from EPPRA’s and other source developers

New features

• Model debris generation from insulator and electrodes

• Code development for non-stationary ionization and excitation