Strongly Multiplexed Micro Plasma Pulse EUV Source with Non-Destructive EUV Radiation Collimating-Focussing Structure

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MPP/PCS Characteristics

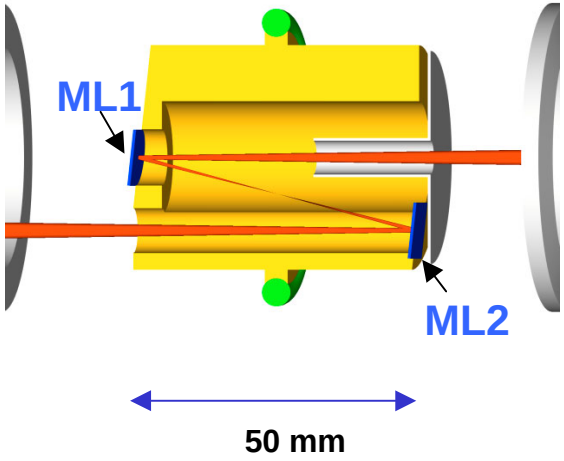
key features

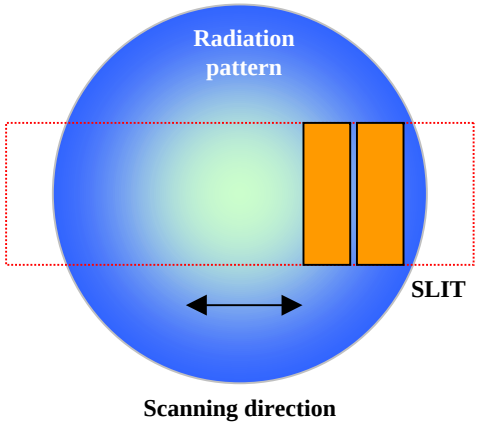
- The Micro Plasma Pulse (MPP) discharge radiation source is a compact, low energy (< 1J), hollow cathode triggered, fast capillary discharge.
- A compact photon collection and projection device based on a plasma collimating structure (PCS) has been developed.
- The PCS produces an equivalent focal spot some 50 cm from the discharge source, with good optical properties, yielding an etendue figure of < 10^{-3}mm^2.sr
- The PCS is generated dynamically with the MPP and is inherently damage resistant; the structure also serves to mitigate debris from the plasma source.
- The combined MPP/PCS demonstrates high in-band EUV collection efficiency at kHz operation.

In-band MPP/PCS Characteristics

measurement system

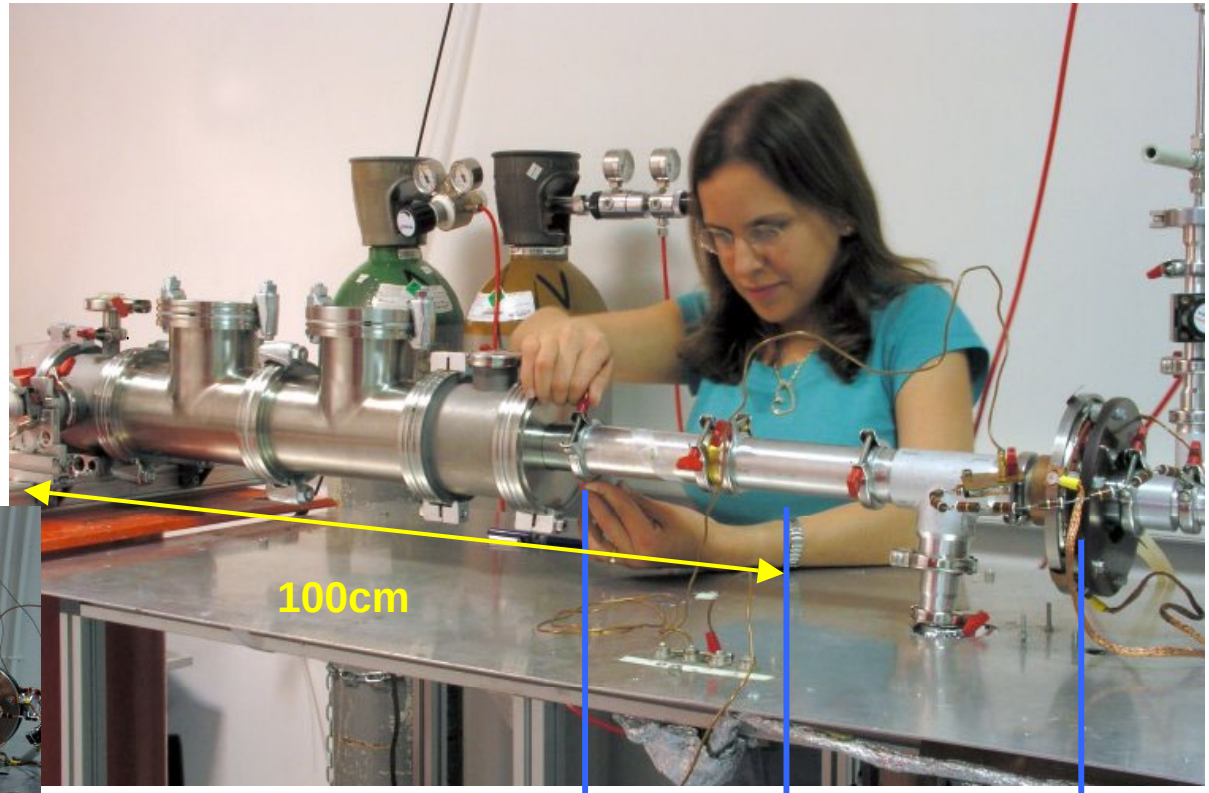
- double flat ML(5º, Osmic, inc.) spectrometer to provide beam imaging of inband EUV signal
- coupled to Scanning Slit system to measure radiation profile at given Z from exit plane of collimator
- slit size 500 μm width, 4.6 mm height effective
- use AXUV100 diode with Zr filter (0.25 μm) behind slit to measure in-band radiation profile

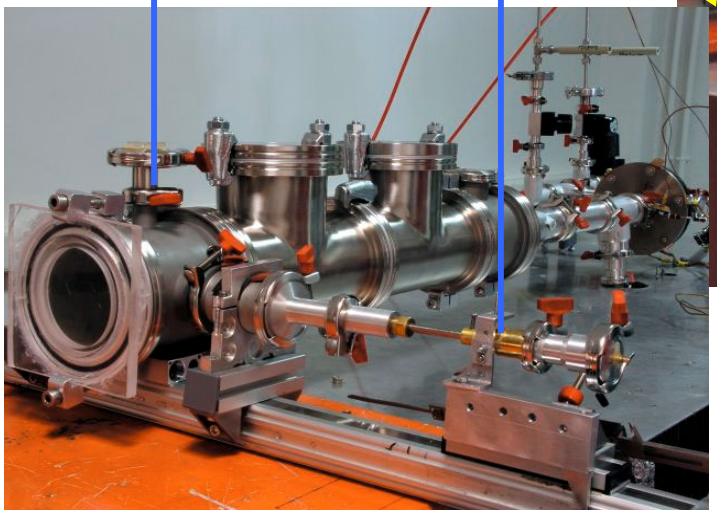




In-band MPP/PCS Characteristics

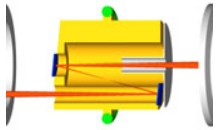
experimental set up





AXUV diode & Slit

Scanning stage



ML spectrometer

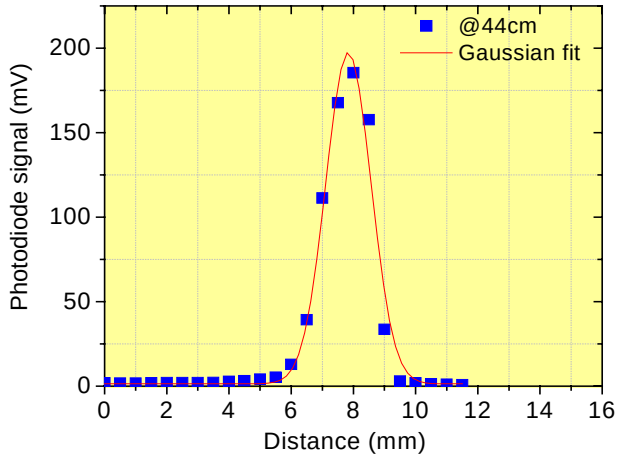
PCS

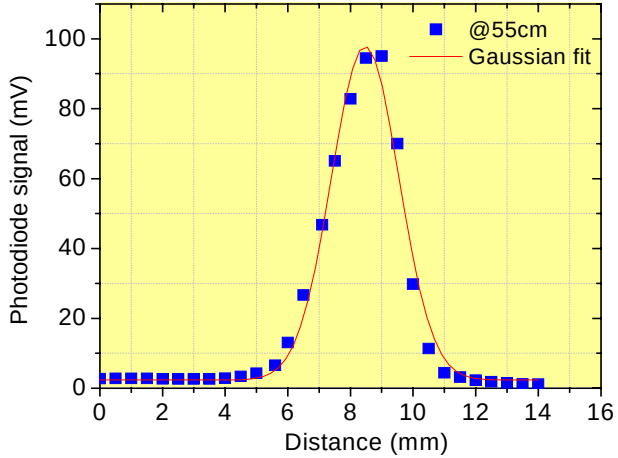
Plasma Collimating Structure

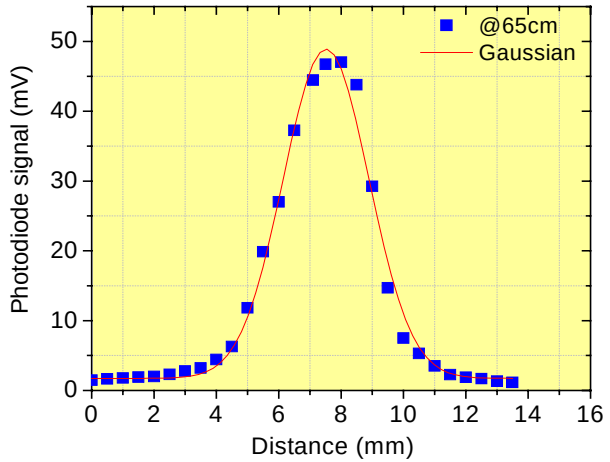
MPP discharge cell

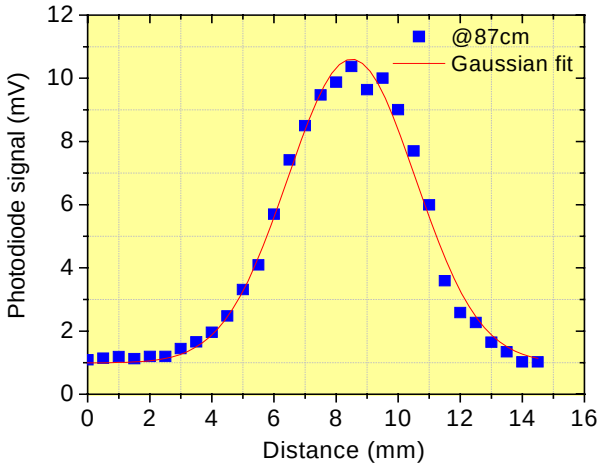
In-band Radiation Measurements

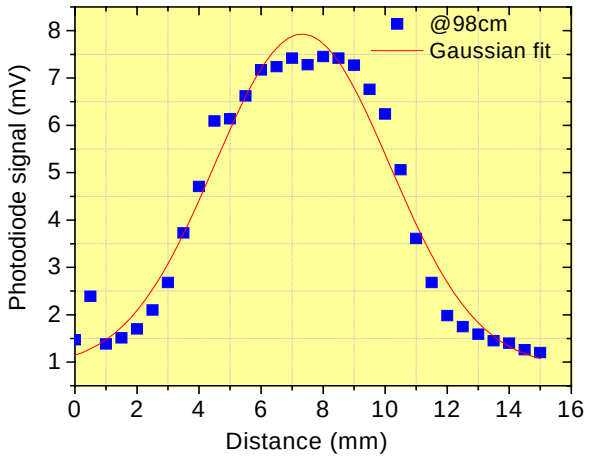
near field (40-100 cm) spatial profile







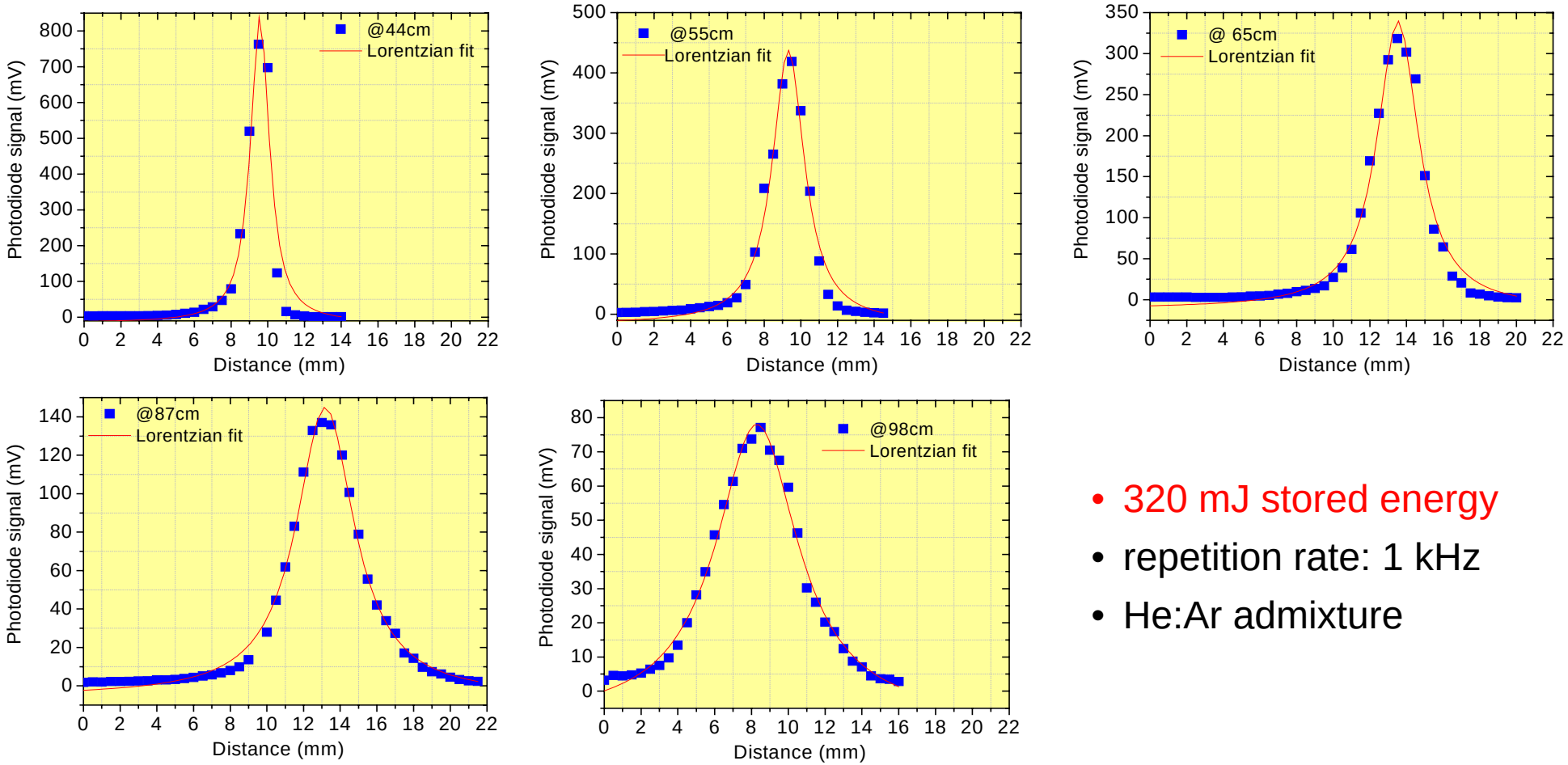




- 100 mJ stored energy
- repetition rate: 1.5 kHz
- He:Ar admixture

In-band Radiation Measurements

near field (40-100 cm) spatial profile



- 320 mJ stored energy
- repetition rate: 1 kHz
- He:Ar admixture

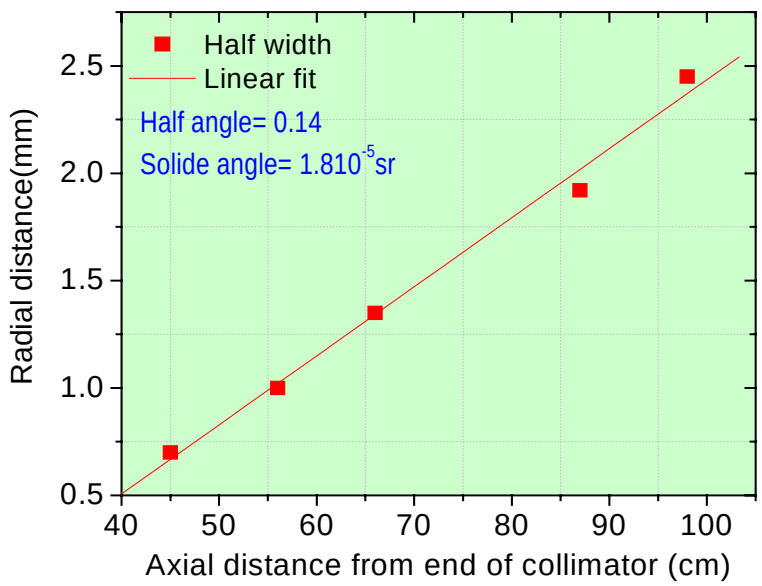
Better collimating properties at higher source power

In-band Radiation Measurements

near field optical properties

Stored energy in discharge cell - **320 mJ**

- single Gaussian profile fitting to obtain radiation half width
- source diameter ($1/e^2$ spot size) 2.5 mm at 44 cm from exit of PCS; 69 cm from plasma source



very small etendue: 8.6 10^{-5} mm^2.sr

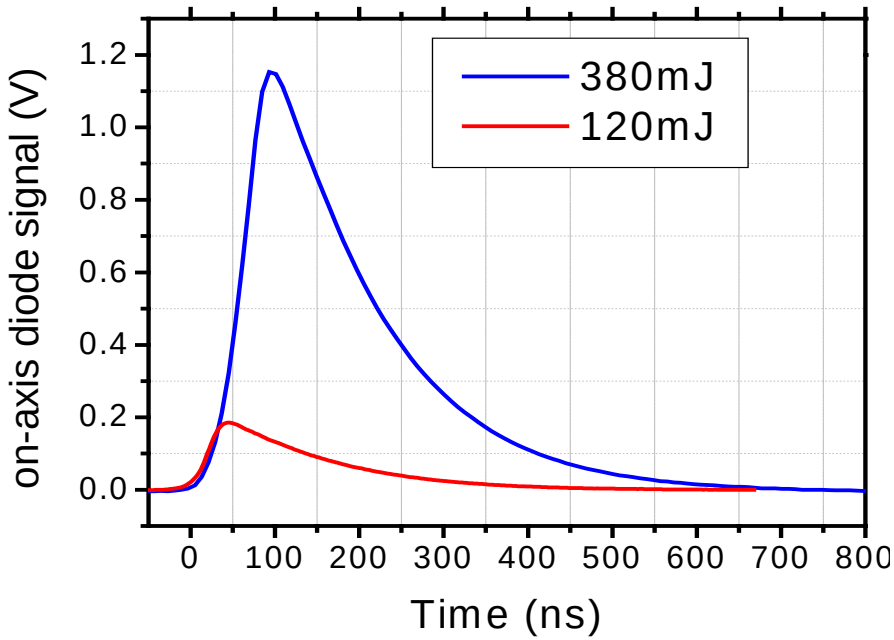
➔ Detected in-band pulse energy in spot : E = 0.70 µJ

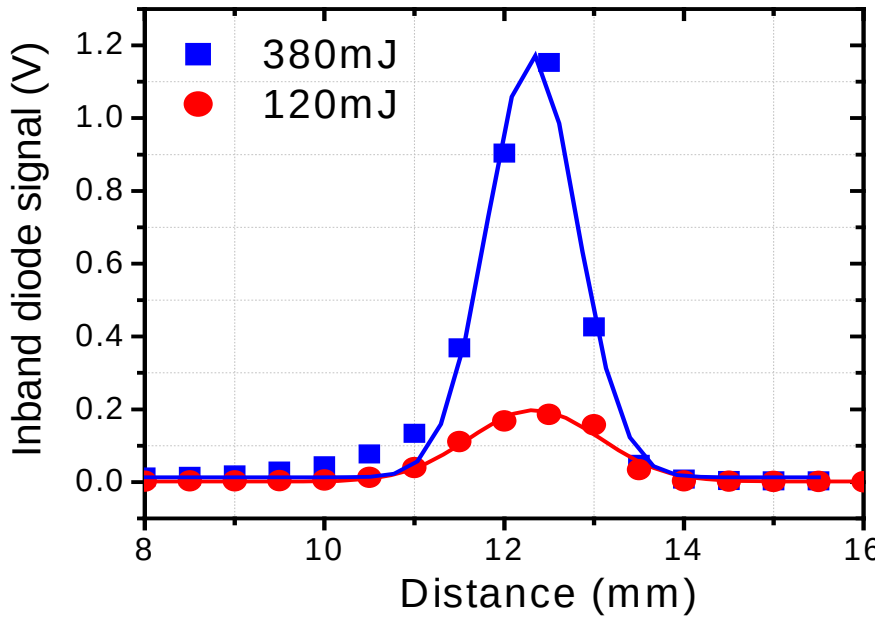
➔ In-band pulse energy fluence: 14 µJ/cm^2

Corresponds to 419 mJ/pulse using "equivalent 2π source" concept !

Scaling up Input Power

spatial and temporal characteristics





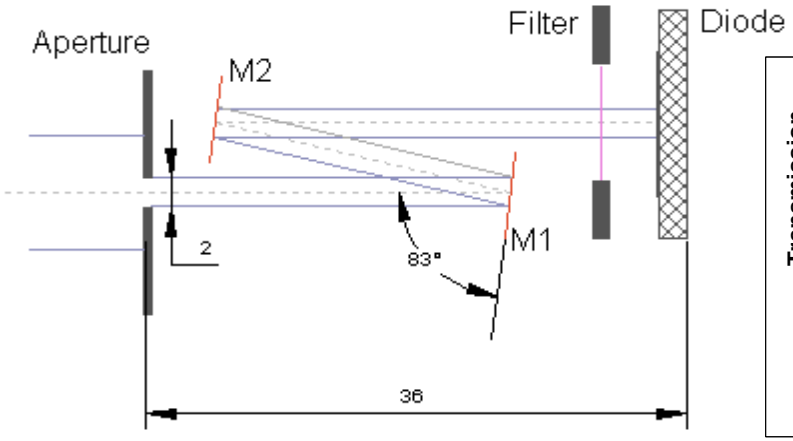
120 to 380 mJ stored energy

- The radiation time duration is longer at higher energy
- The spot size is smaller at higher energy

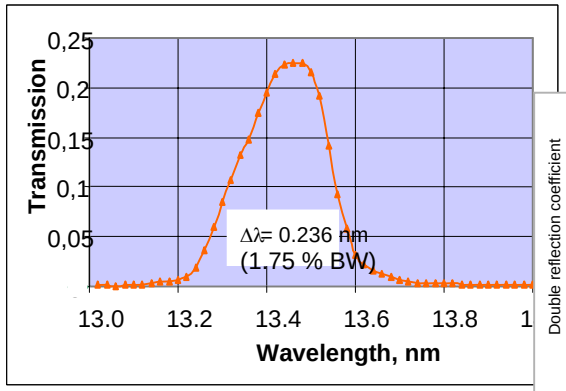
MPP/PCS collimated EUV source is scalable

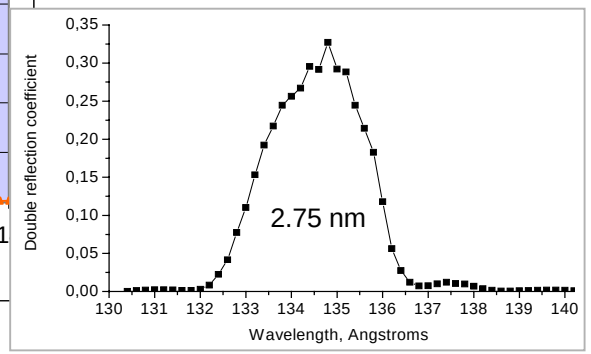
Independent Measurements

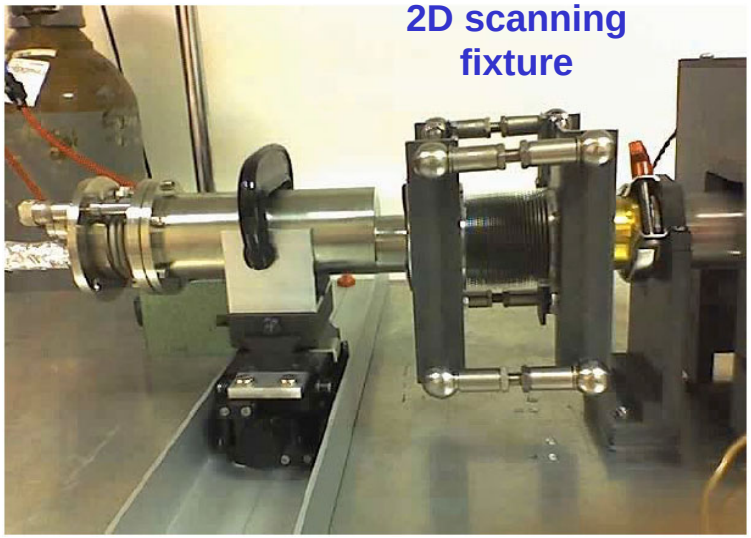
PCS performance measured by Phystex



In-band tool







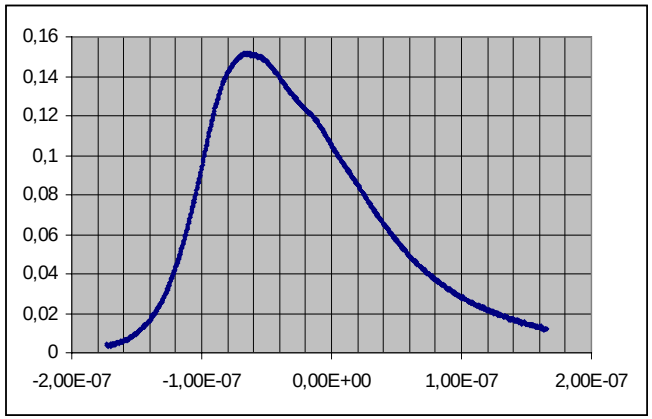
Conditions for 1-D and 2-D tool

- Aperture area: $a = 11\ mm^2 \rightarrow 3.2\ mm^2$
- Filter transmission: $T_F = 0.2 \rightarrow 0.42$
- Transmission of double ML mirrors $T_M = 0.225 \rightarrow 0.3$

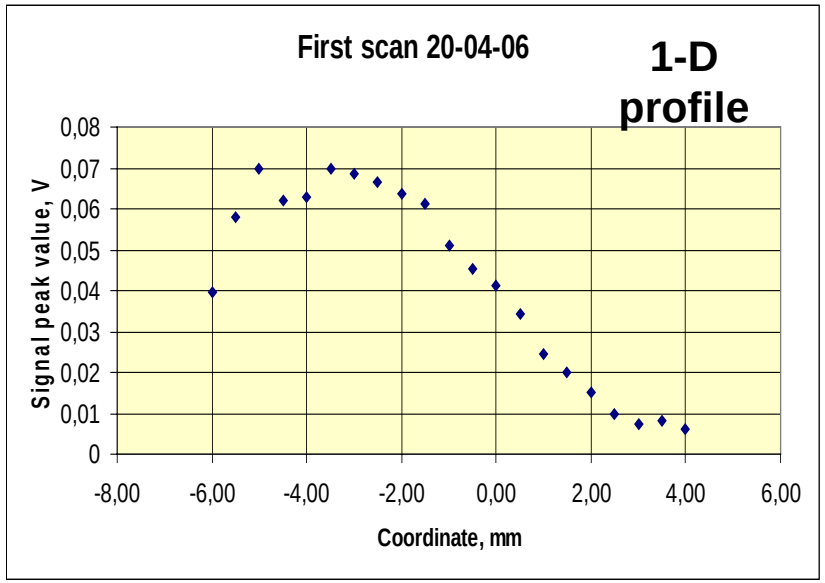
Measurements with Phystex in-band tool

1-D and 2-D scans

Stored energy in discharge cell - **100 mJ**



EUV diode signal measured from Ar:He plasma at distance 50 cm



➔ Detected in-band pulse energy through aperture: E = 0.1 μJ

➔ In-band pulse energy fluence : 0.9 μJ/cm^2

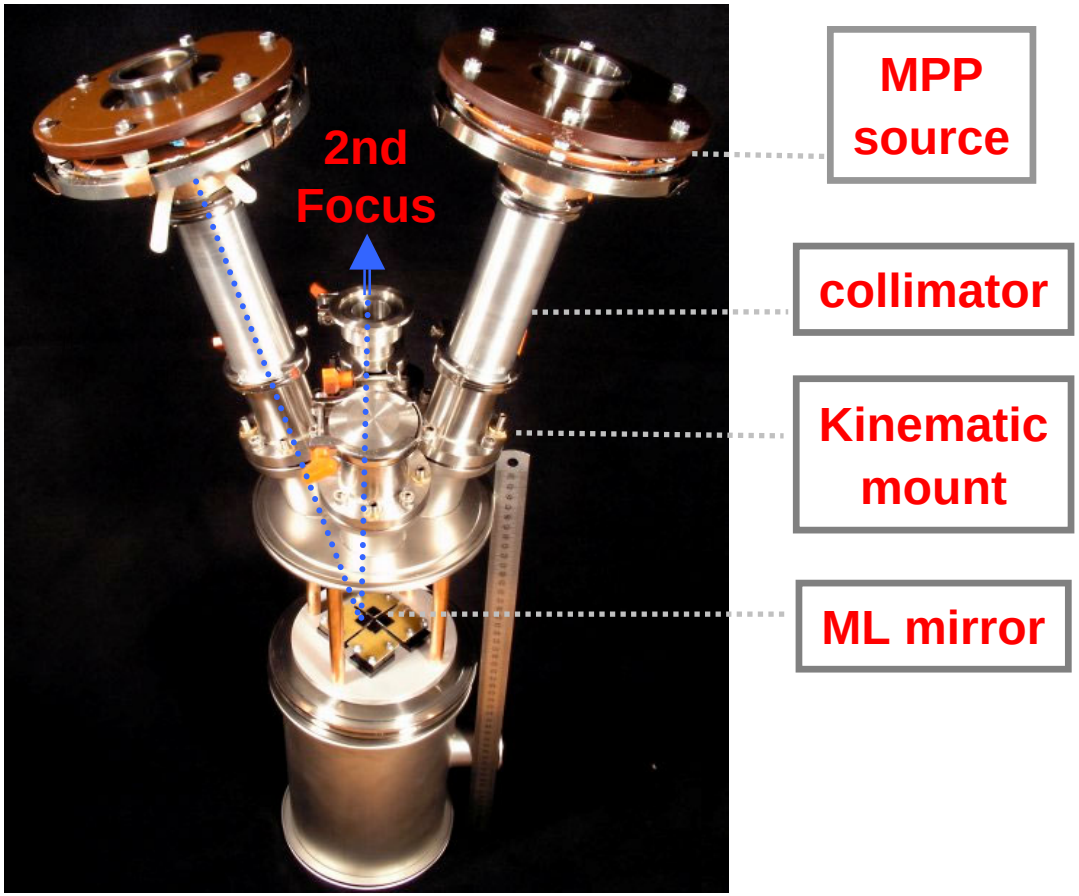
Independent measurements by Phystex confirmed PCS operation

Multiplexed MPP/PCS Source

4 units - current implementation

Features

- 4 separate MPP sources (2 shown assembled)
- HV drives operate in atmosphere
- very compact common vacuum chamber for beam multiplexing
- sequential and/or parallel operation for output control
- up to 12 kHz multiplexed output
- clean output beam (fast ions/particles free)
- ideal metrology tool



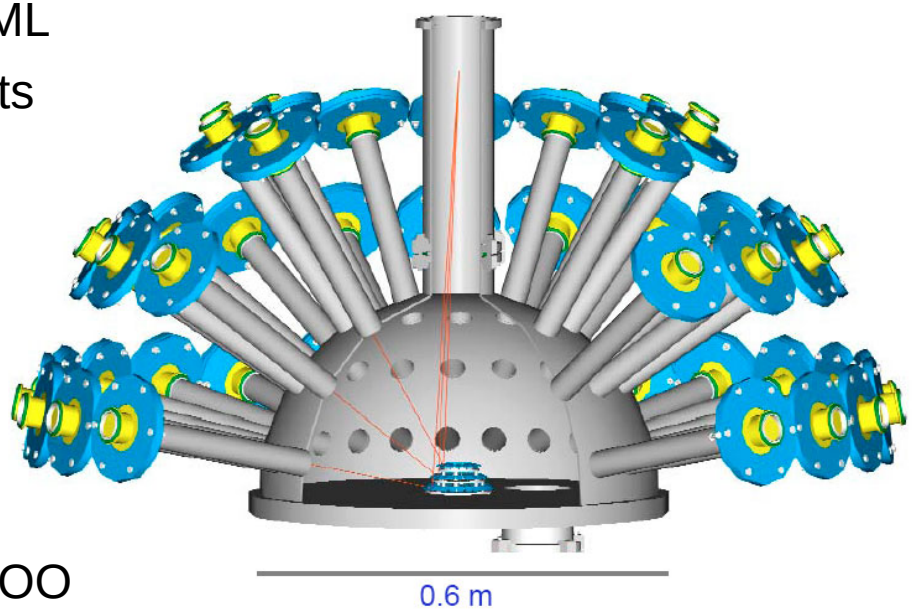
Multiplexed MPP/PCS Source

60 units - HYDRA 60 HVM tool design

Features

- 60 separate MPP/PCS sources
- each source operates at 5 kHz to provide 5 W out of PCS (1 mJ in-band/pulse) at an input power of 8 kW
- 3.5 W projected to IF through single planar ML
- 210 W in-band total available from all 60 units
- combined source etendue below 0.3 mm^2.sr
- total electrical input 480 kW
- total anode surface > 200 cm^2
- sequential operation of group of sources to decrease duty cycle of each source
- failure of 1 unit will not effect a shut down
- scalable HVM performance with attractive COO

HYDRA 60



Z* Blackbox Modeling Engine

for EUV plasma sources

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.

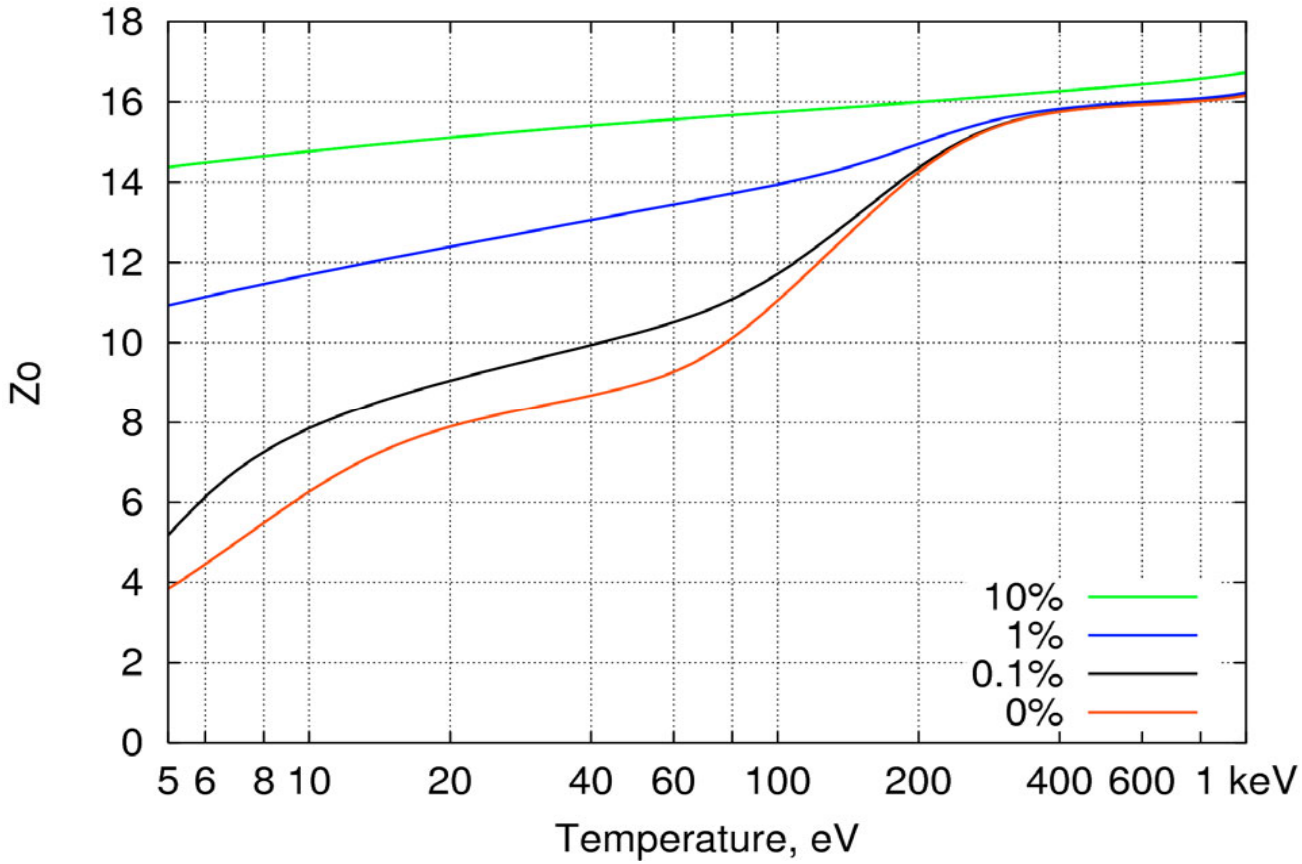
In the Detailed Physics mode, non-stationary, non-equilibrium radiation physics have been introduced to allow the modelling of transient plasmas in DPP and LPP in 2D geometry. Detailed Physics mode has extensions for spectral transfer and thermal analysis post-processing.

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.

Hollow Cathode Electron Beam

increasing ionization degree in plasma



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

Energy of fast electrons
E = 5 keV

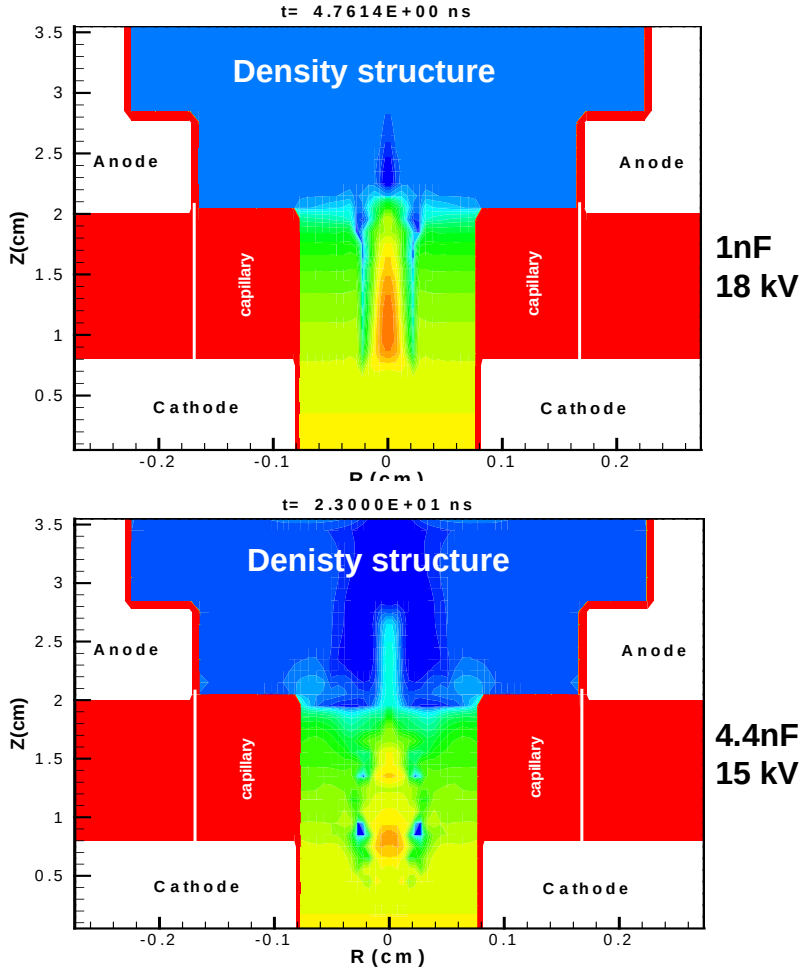
Relative concentration
ξ = 0.1, 1, 10%.

Z*BME

Collimator Performance

modelling

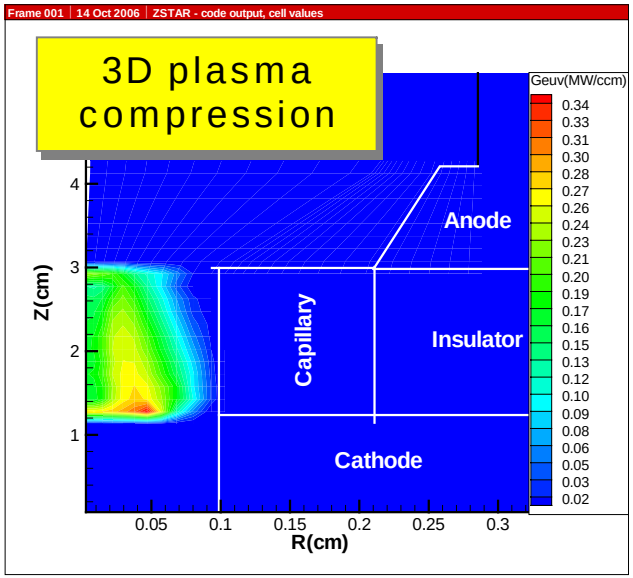
- MPP radiation guiding (first collimation) through plasma density profile structure
- optimal operating pressure gradient and energy input rate for efficient guiding
- agreement with 3-D pinch compression demonstrated in Z*BME™ simulation



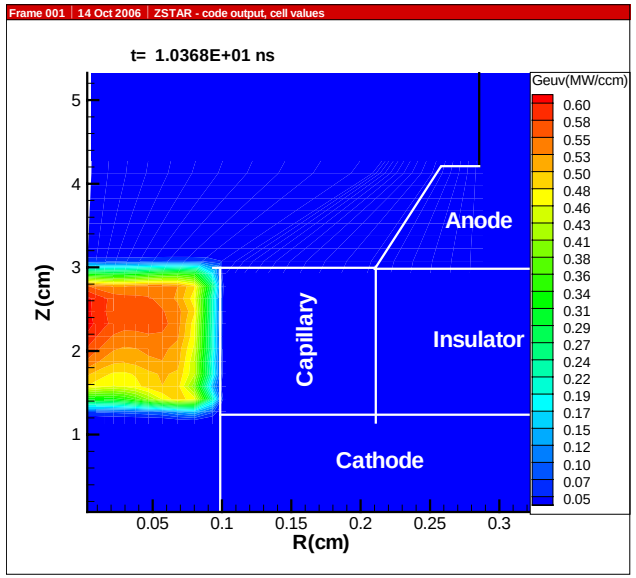
Z*BME

MPP Source

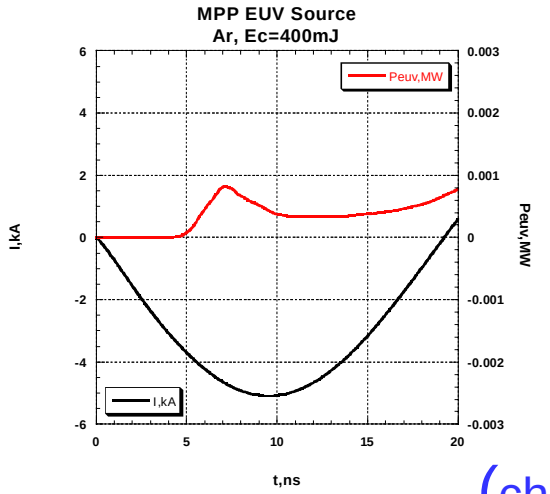
operation with He:Ar and He:Xe



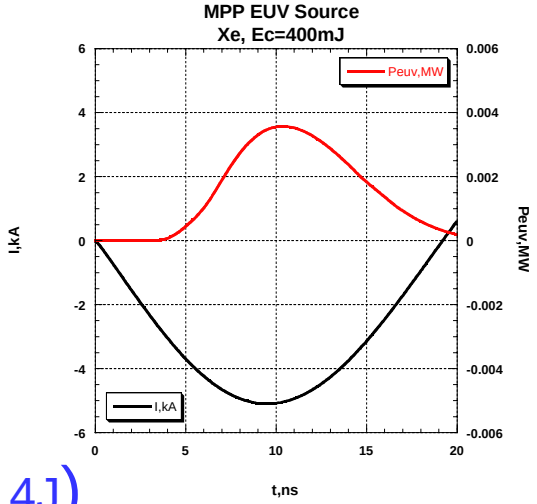
EUV emissivity distribution



He:Ar



current & EUV emission



He:Xe

(charge energy 0.4J)

Plasma-electrode interaction mechanisms

thermal considerations

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

thermal instability:

$$\sigma(T) \sim \sigma_0 \frac{\theta}{T} \qquad c_v \frac{\partial T}{\partial t} = \frac{j^2}{\sigma}$$

$$T = T_0 e^{\int \gamma \, dt} \qquad \gamma = \frac{j^2}{\sigma_0 \theta c_v}$$

- 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).

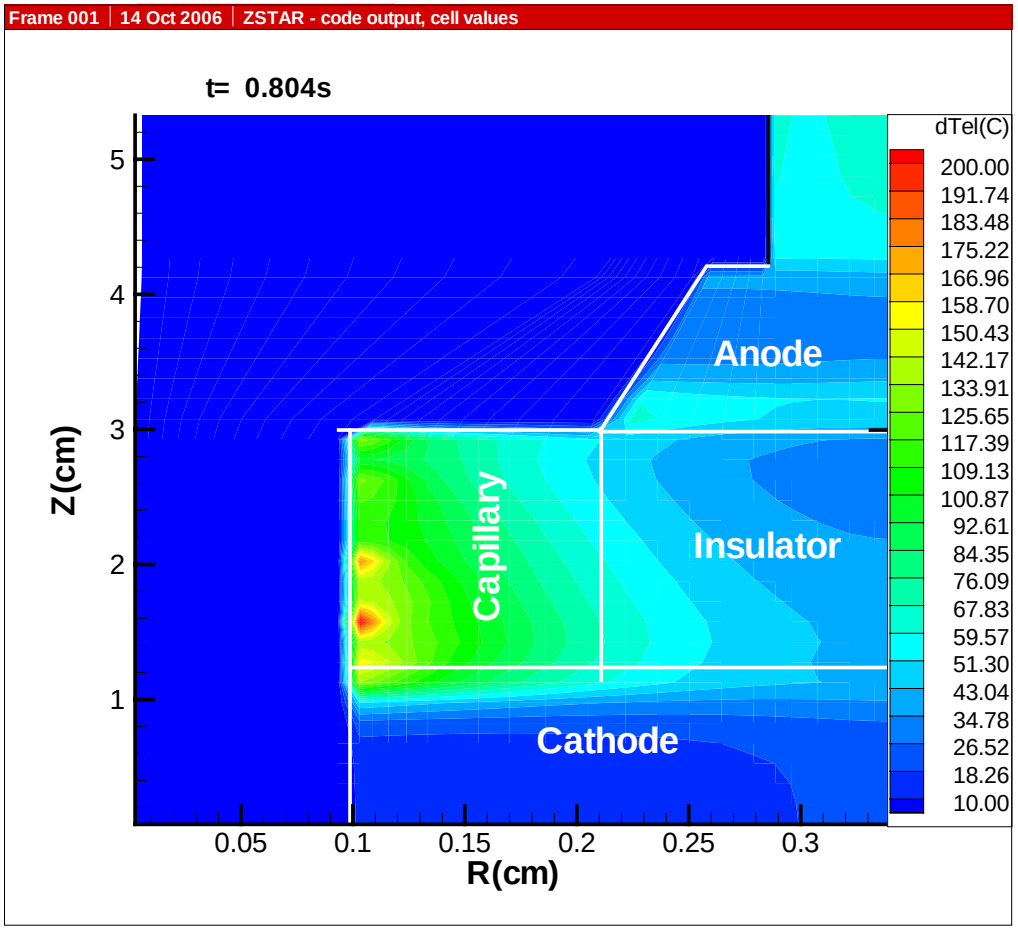
Z* BME

Heat loading on electrodes

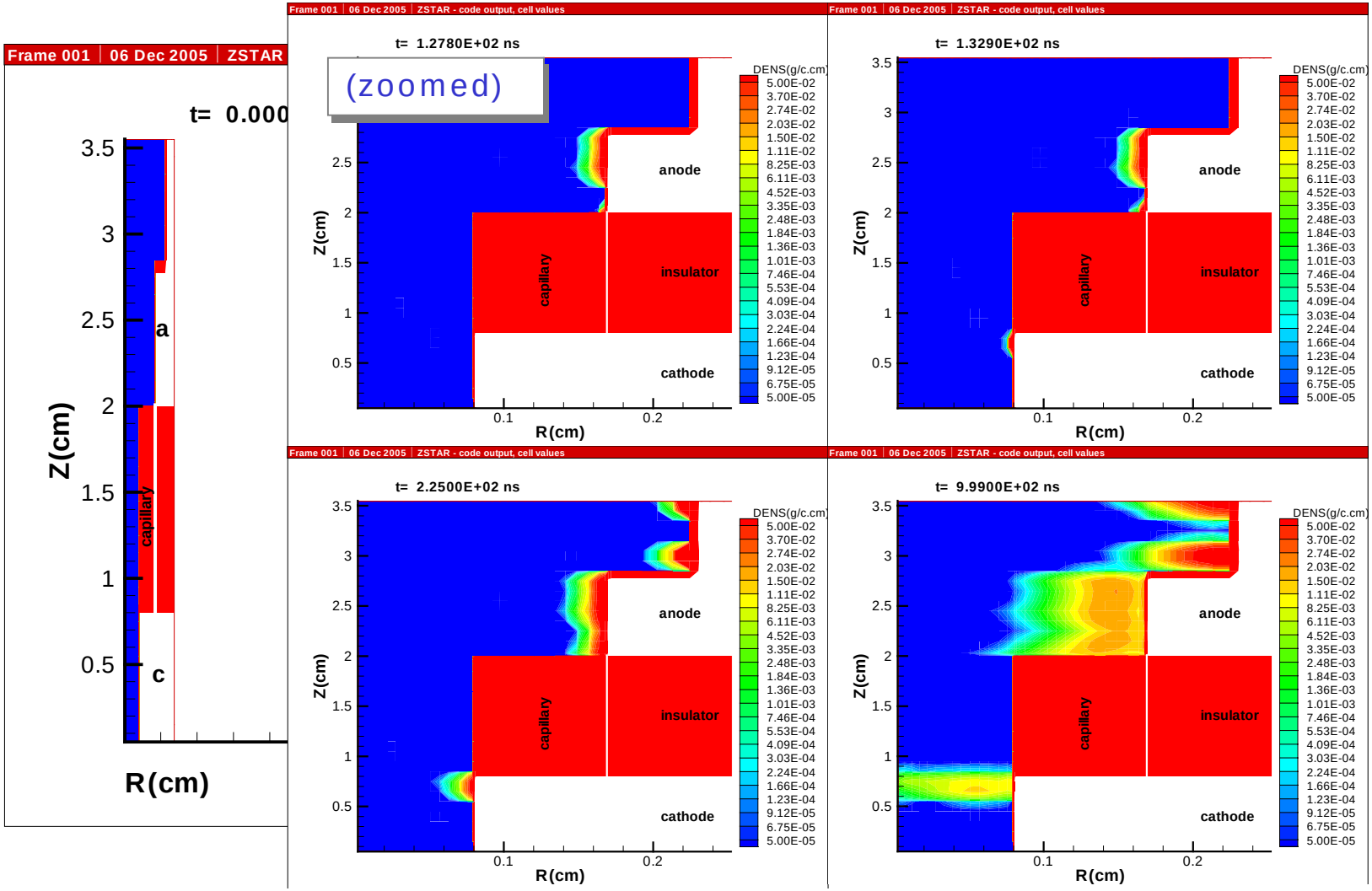
charge energy 0.4J/pulse, frequency 3kHz

Low energy discharge unit provides:

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



Z* BME Debris generation from electrodes modelling



Summary

PCS/MPP performance

- EPPRA has demonstrated a high frequency photon collection and projection device based on a plasma structure. The device is inherently damage resistant.
- Measured in-band EUV energy fluence of 14 $\mu J.cm^{-2}$ per pulse at 320 mJ energy stored (for Ar:He) at 69 cm from the plasma discharge source, with a source etendue < 10^{-4} $mm^2.sr$.
- Fluence value would correspond to "equivalent 2π source" 419 mJ/pulse for charge energy 320mJ, indicating very high focussing efficiency of the plasma collimating structure is realised.
- Use of Z*BME has provided key insight into thermal loading and electrode erosion issues, allowing the discharge source structure to be optimized.
- The compact collimated source concept opens up the possibility of developing a fully scalable, compact, strongly multiplexed EUV source, delivering clean photons at the IF with a power level well above the 200 W in-band required for an HVM tool.

Acknowledgement

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