Progress in modelling of high intensity radiation plasma sources

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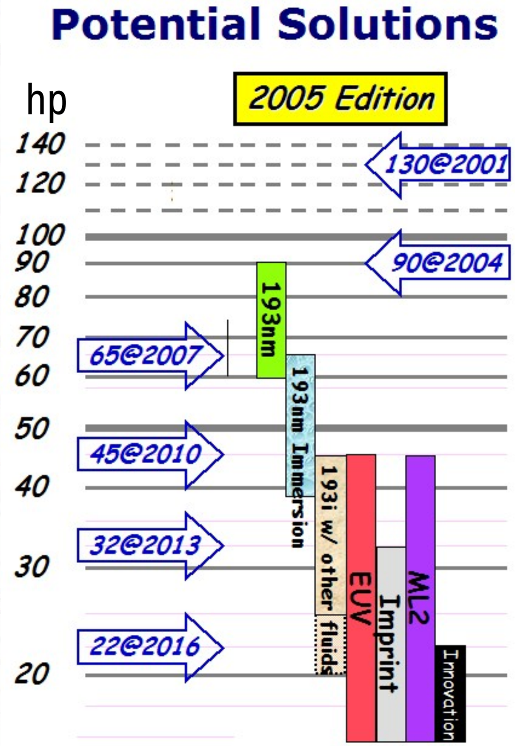
fire
Fluid, Ions and Radiation Ensemble
in Integrated Plasma Modelling

EUV Sources for EUV Lithography



Diffraction restricts the resolution

$$r \ge k_1 \frac{\lambda}{NA}$$

$\lambda \Rightarrow$ 13.5nm ($h\nu$=92eV)

$\delta\lambda/\lambda \Rightarrow$ 2%

Nano-Age World

NOW
EUV for HVM
beyond 16 nm

- For HVM - 200-500 W of in-band power @ IF with etendue < 3mm^{2}sr
- For mask inspections ABI→AIMS→APMI – 10 →100 →1000 W/mm^2·sr

Sn, Xe… high energy density plasma (T_e=20-40eV) radiates at EUV range

LPP & DPP can produce a HED plasma

Next Generation Modelling Tools

- FP7 IAPP project FIRE

- Theoretical models and robust modeling tools are developed under international collaboration in the frames of European FP7 IAPP project FIRE

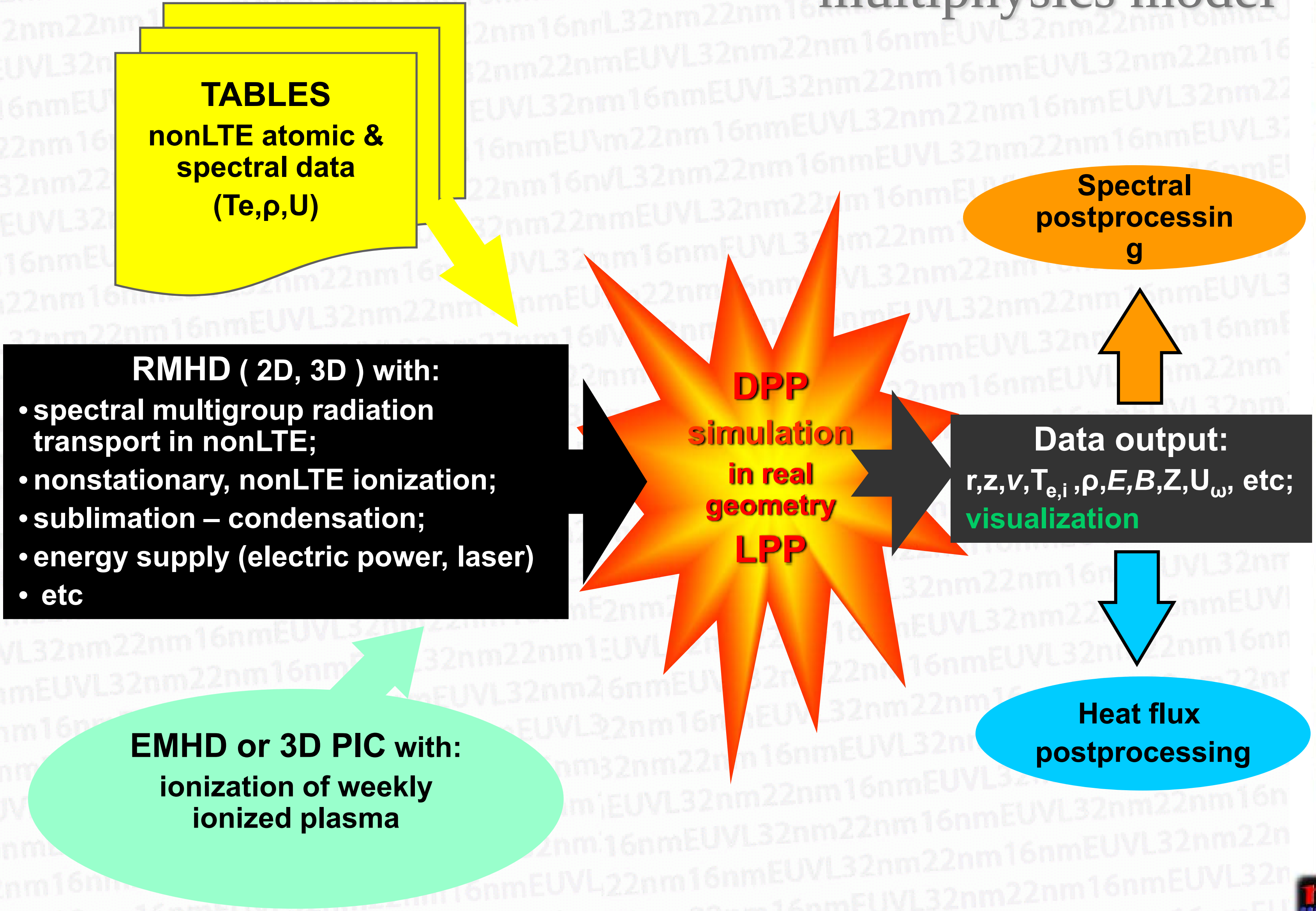
- The FIRE project aims to substantially redevelop the Z* code to include improved atomic physics models and full 3-D plasma simulation of
  - ✓ plasma dynamics
  - ✓ spectral radiation transport
  - ✓ non-equilibrium atomic kinetics with fast electrons
  - ✓ transport of fast ions/electrons
  - ✓ condensation, nucleation and transport nanosize particles.

- Modelling can be the key factor to scientific and technological solutions in EUVL source optimization with fast particles and debris to solve current EUVL source problems as well as extending their application to 22nm and beyond.

- The research and transfer of knowledge is focused on two major modeling applications;
  - ✓ EUV source optimization for lithography and
  - ✓ nanoparticle production for nanotechnology.

- Theoretical modelling will be benchmarked by LPP and DPP experiments

ZETA → Z^* RMHD Code → Z^* BME multiphysics model



TABLES
nonLTE atomic & spectral data
(Te,ρ,U)

RMHD (2D, 3D) with:
- **spectral multigroup radiation transport in nonLTE;**
- **nonstationary, nonLTE ionization;**
- **sublimation – condensation;**
- **energy supply (electric power, laser)**
- **etc**

EMHD or 3D PIC with:
ionization of weekly ionized plasma

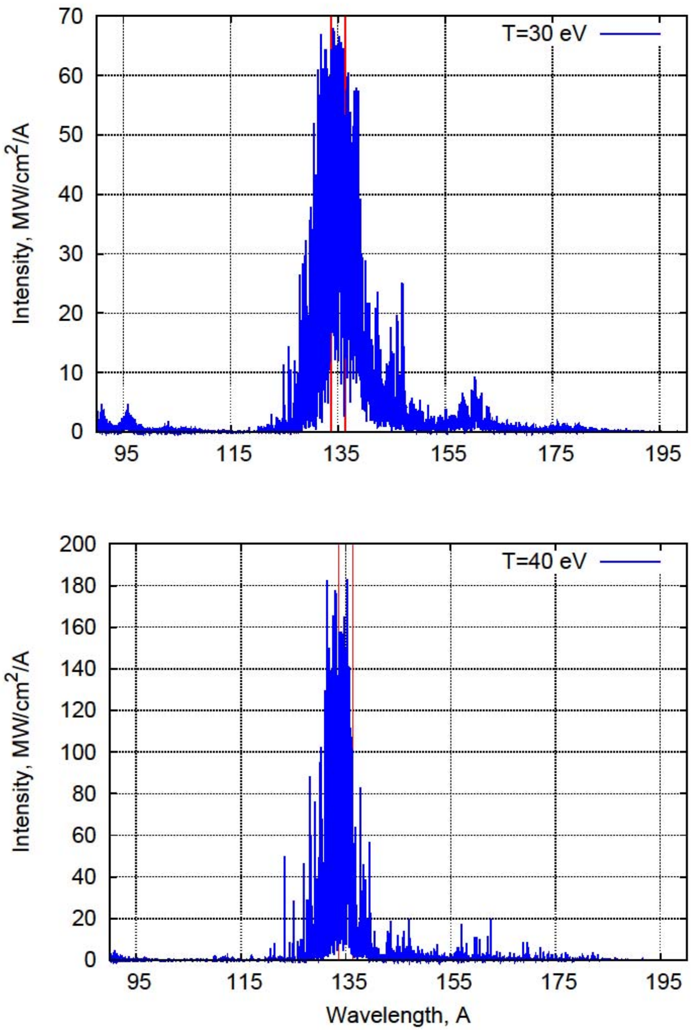
DPP
simulation in real geometry
LPP

Data output:
$r,z,v,T_{e,i},\rho,E,B,Z,U_{\omega}$, etc;
visualization

Spectral postprocessing

Heat flux postprocessing

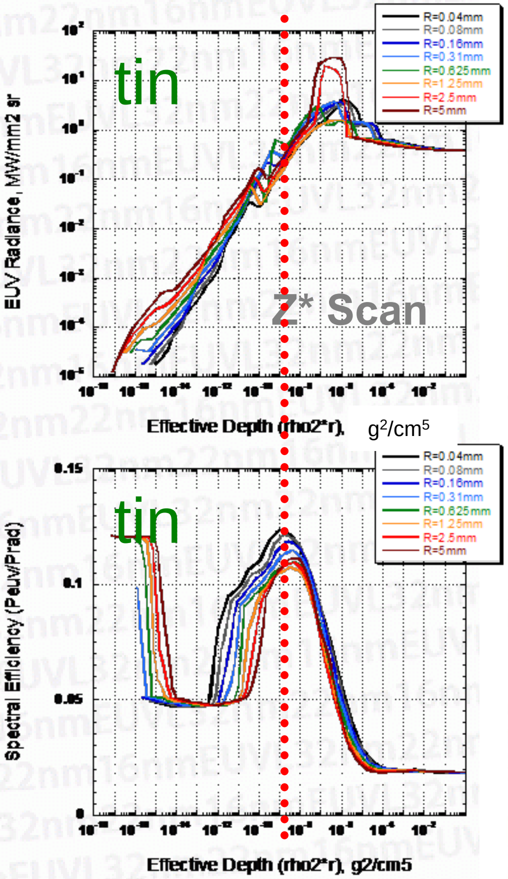
EUV Brightness Limit of a Source



Detailed spectra from tin plasma with radius R=100 μm and $n_e=10^{19}$ cm^{-3}

Spherical model of tin plasma EUV source

The radiation self-absorption limits the in-band EUV radiance from the plasma, and the etendue constraint limits the usable power at IF of a conventional single unit EUV source



RMHD scan for tin plasma optimized by radius, temperature and density [AL10]

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Nano-UV: High Brightness EUV Source

capillary discharge micro-pulsed-plasma

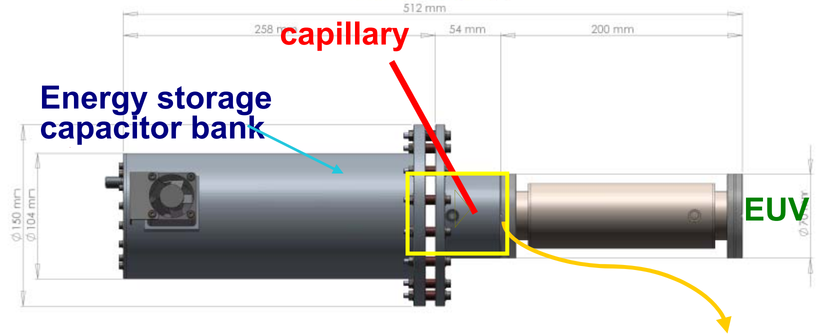
Power source

Charge energy	0.2 – 0.5 J
Current	5 - 10 kA
Pulse	~10-20 ns
Capillary dimension:	∅ 1.6 mm L = 12-18 mm

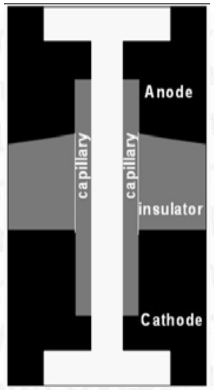
Various electrode geometries

Gas:

0.01-1Torr gradient He;
Xe, N_2, Ar, Kr,, … admixtures
(for narrow-band radiation source)



Experimental set up



Example of simulated geometry

Capillary discharge dynamics & emission features:

E-beam, plasma channelling (ε>>1)

Volumetric MHD compression (skin depth >>plasma diameter)

Highly ionized ions (fast electrons)

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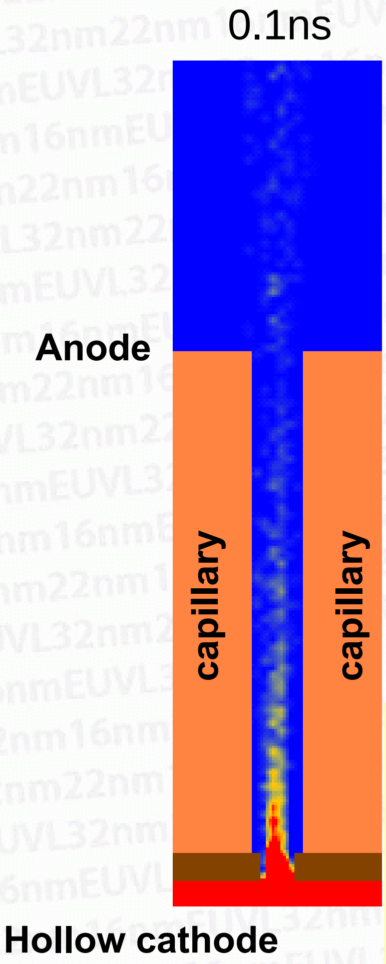
Capillary Discharge EUV Source

- fast electrons 3D-PIC modelling



Electron beam in the HC capillary discharge

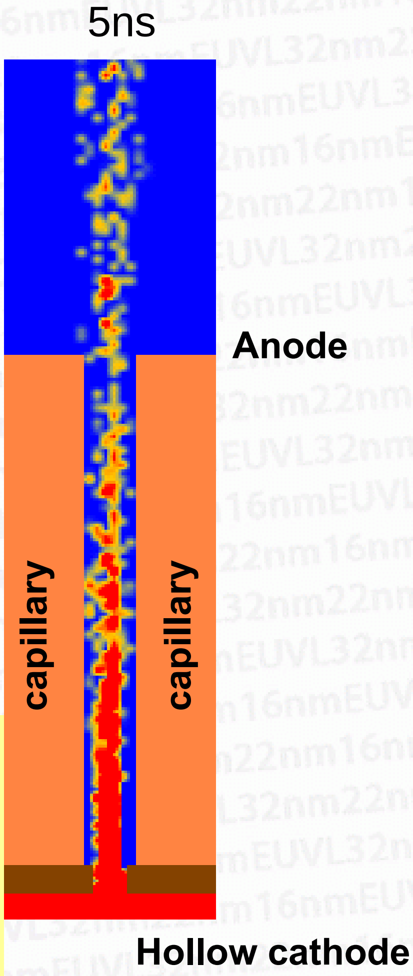
⇒ run-away electrons

⇒ voltage drop dips into HC

⇒ e-beam concentration

⇒ e-beam-gas ionization

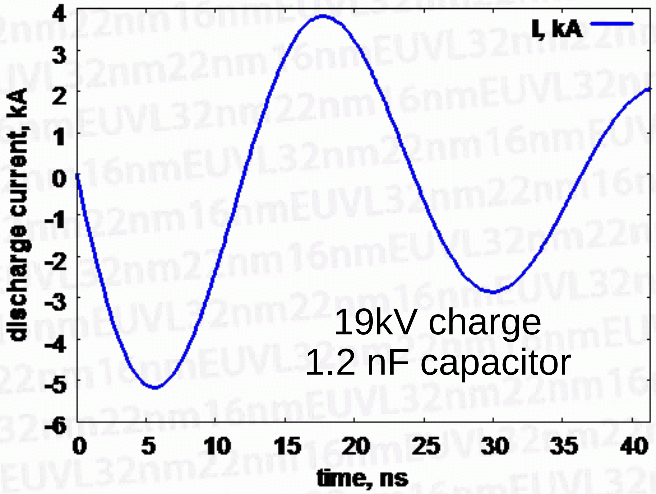
In the first few nanoseconds, run-away electrons from the hollow cathode generate a tight electron beam ionizing a channel in the gas



Capillary Discharge EUV Source

resistive regime

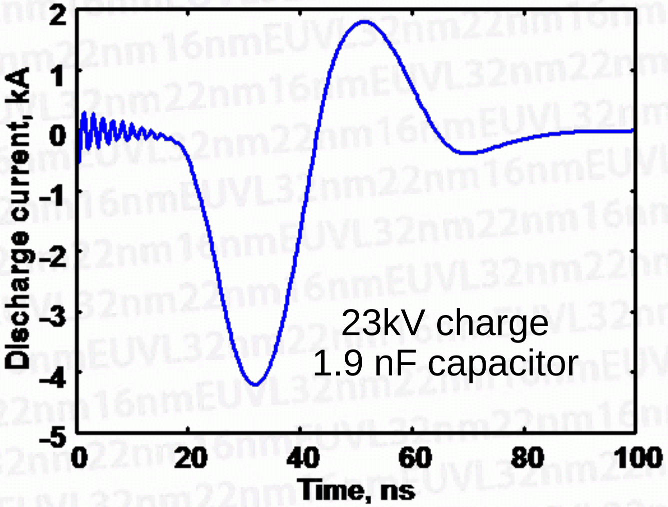
Inductive regime



19kV charge
1.2 nF capacitor

Nitrogen –
buffer gaz

Resistive regime



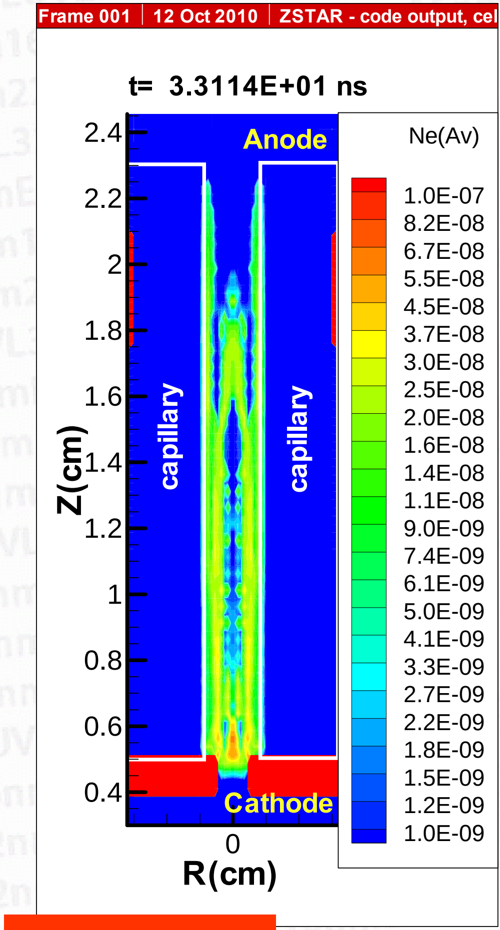
23kV charge
1.9 nF capacitor

In a resistive regime of capillary discharge, the high joule dissipation in the tight conductive channel produced by hollow cathode electron beam creates an efficient mechanism of plasma heating and EUV or soft X-ray emission consequently.

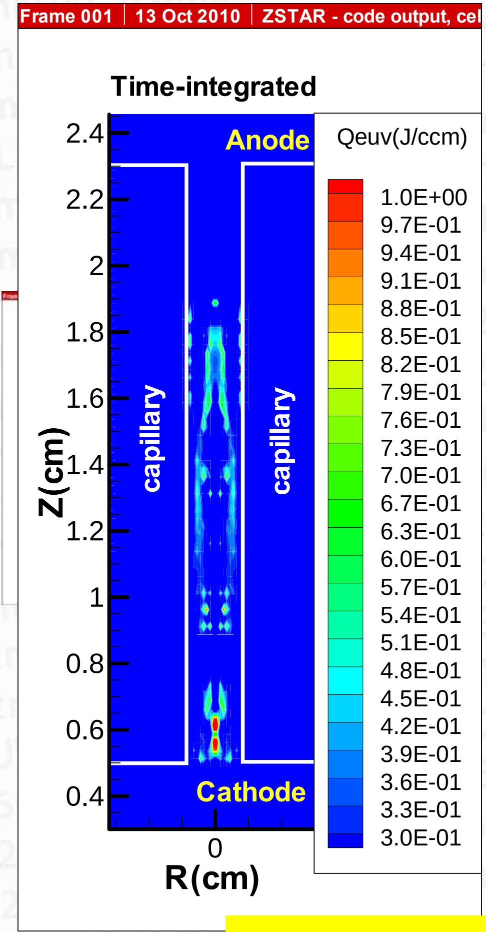
Also, fast electrons increase the ionization degree of heavy ion (Xe,…) plasma increasing eo ipso EUV yield.

Capillary Discharge EUV Source

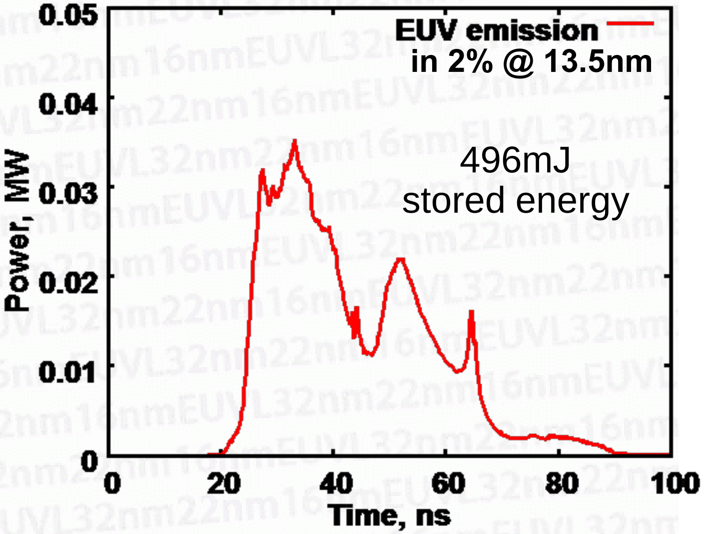
dynamics & EUV emission



3D volumetric compression



EUV source cross-section



At EUV emission maximum:

$N_e=2\text{-}3\cdot 10^{16}\,\text{cm}^{-3}$,

$T_e=25\text{-}40\,\text{eV}$.

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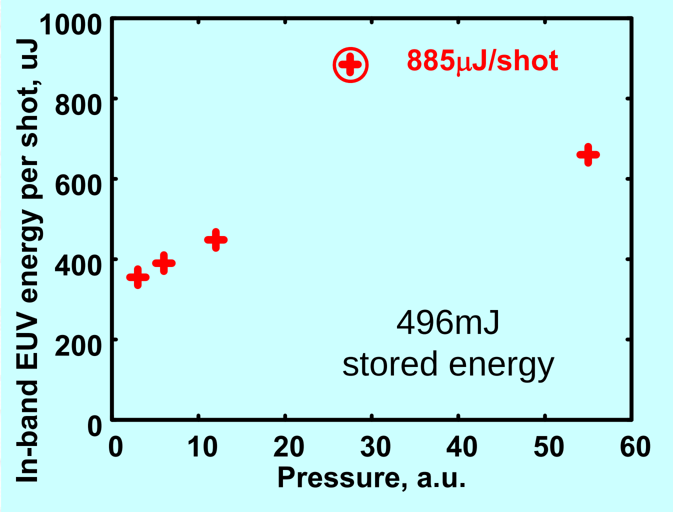
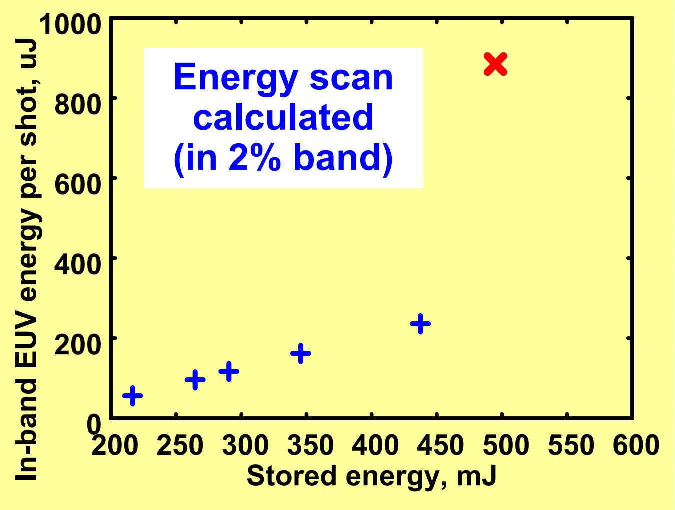
Gen II EUV Source

- characteristics & optimization from Z* modelling



Optimization
by gas mixture
pressure

EUV source
scan by stored
electrical energy



Calculated EUV brightness is up to 10 W/mm^2 sr kHz

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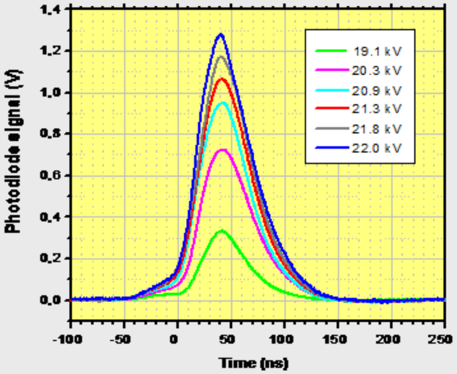
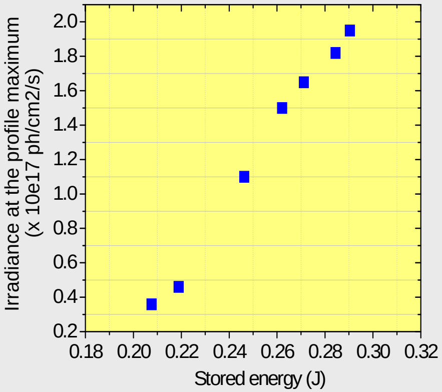
Progress in experiment

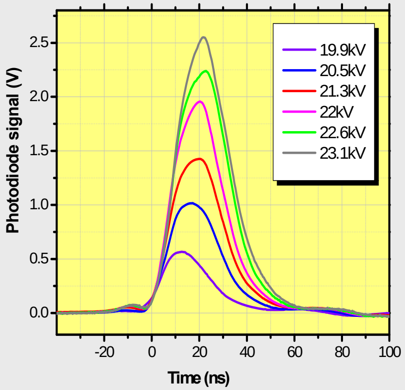
- irradiance vs stored energy

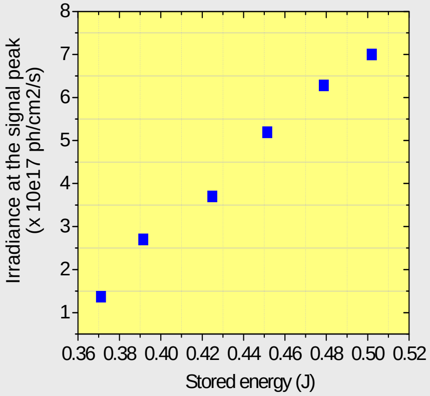
Results presented at 2010





Current Results





At same operating voltage

- ✓ **1.5 time increase on the stored energy**
- ✓ **Improvement on the gas mixture and flow rate**

⇩

- ✓ **2.5 fold increase in the irradiance**
- ✓ **2.5 fold increase on power**

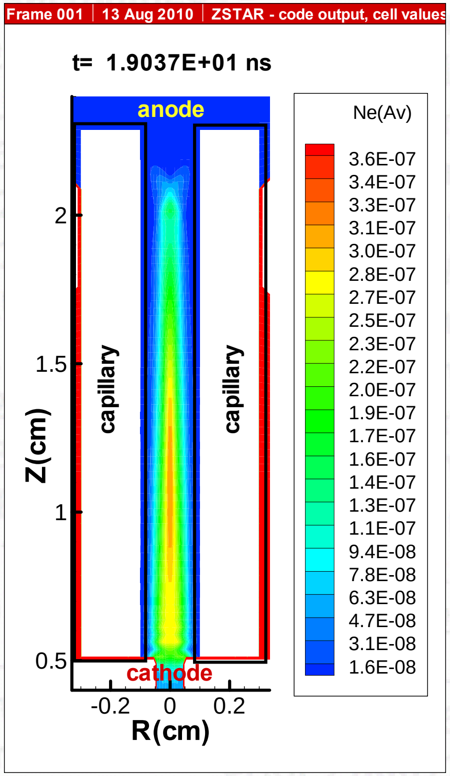
And more, with tin alloy cathode (in the presentation P27) :

- ✓ **2 fold increase in the irradiance**
- ✓ **3 fold increase on power**

MPP source for soft x-ray microscopy

Z*-code modelling

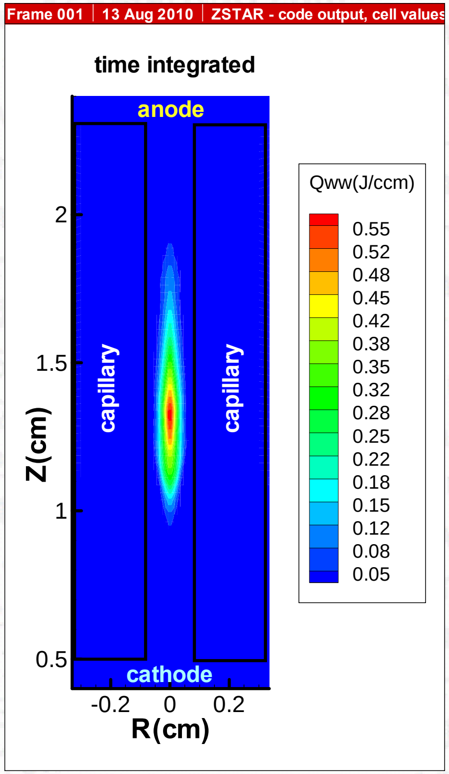
Nitrogen plasma at emission maximum



0.48J/pulse charge

Fast electrons induce discharge in 3-D volumetric compression regime

Time integrated image of soft x-ray (400 - 600eV) source

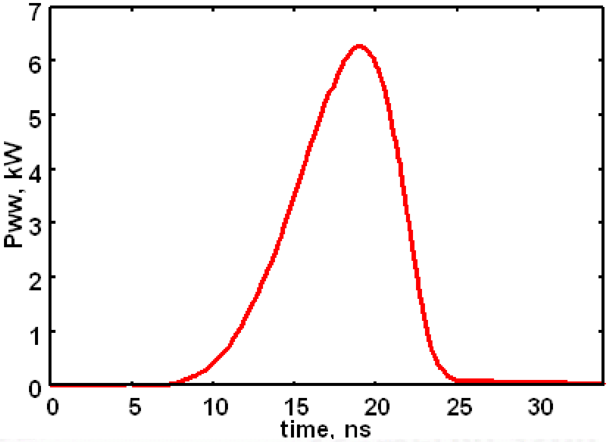


$\langle Z \rangle \approx 4\text{-}5$

$T_e = 45 - 55\text{eV}$

$n_e \approx 2\cdot10^{17}\text{cm}^{-3}$

Soft x-ray pulse

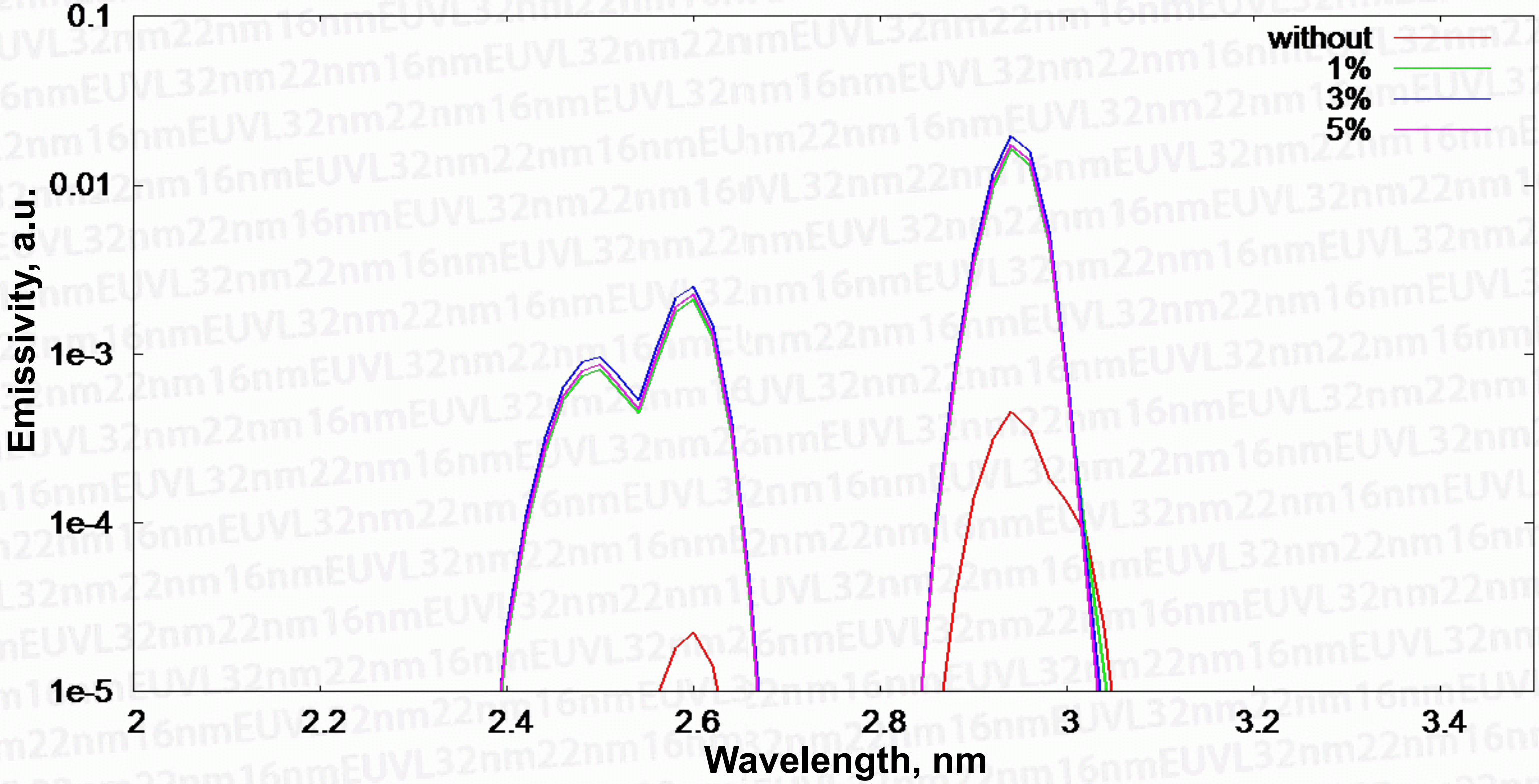


Nitrogen: He-like and H-like

Fast Electrons

enhance soft X-ray radiance of nitrogen plasma

- Non-equilibrium plasma kinetics



Line emission spectra of Nitrogen from non-equilibrium plasma at T=45 eV with various portions (1% to 5%) of fast electrons with 5 keV energy in comparison with emission spectrum of equilibrium plasma at the same temperature. Electron density $n_e = 10^{17}$ cm^{-3}.

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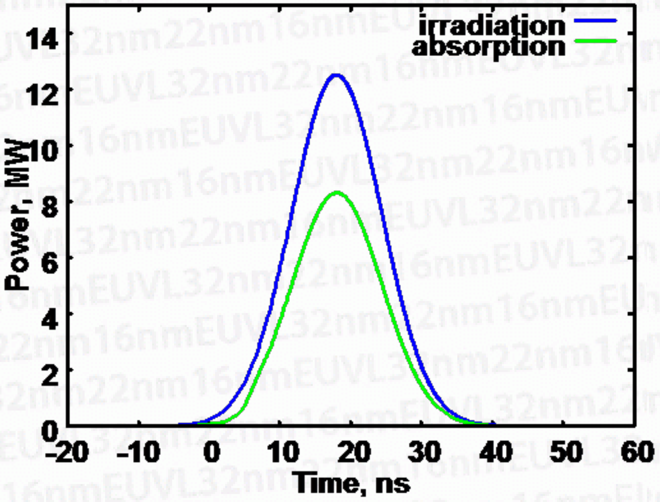
LPP Dynamics

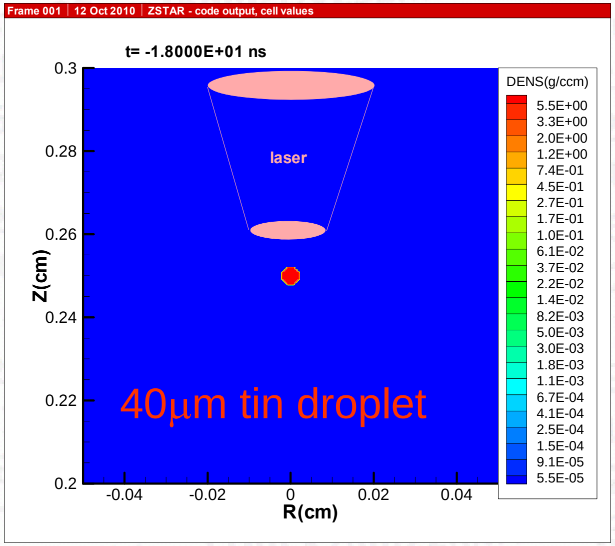
under CO_2- laser pulse



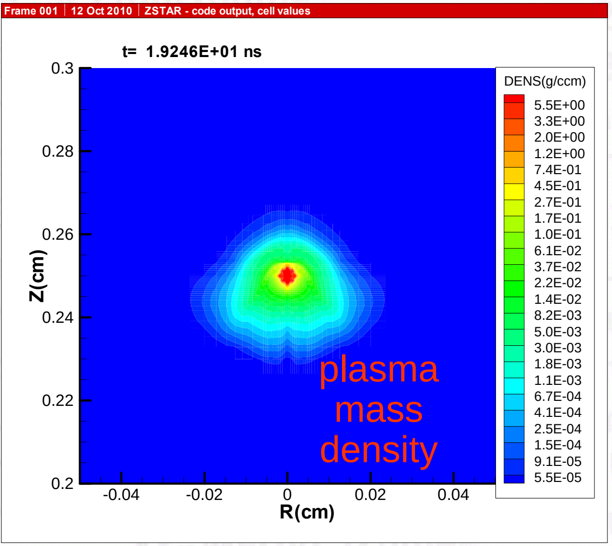
CO_2-laser pulse:

Pulse energy	200mJ
Pulse duration	15ns FWHM
Focal spot size	200 µm

Loses: reflections and large focal size at initial moment



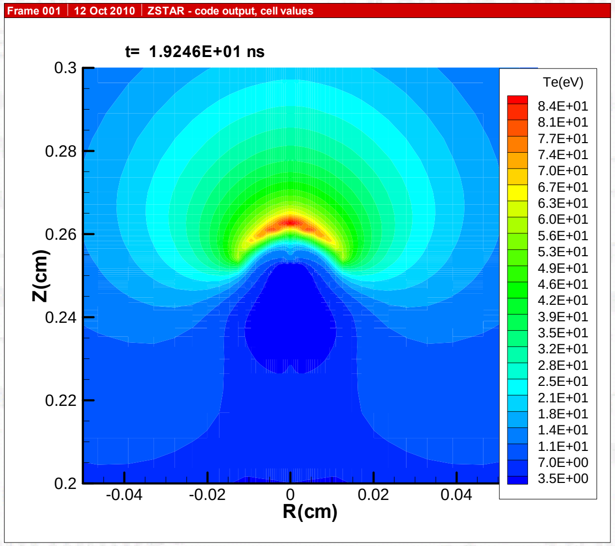
40µm tin droplet

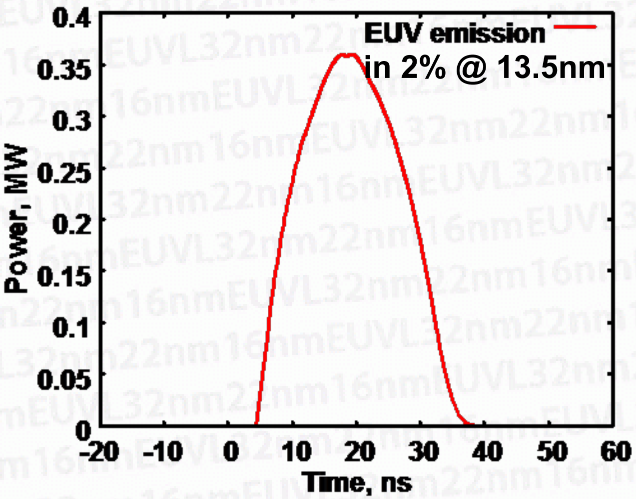


plasma mass density

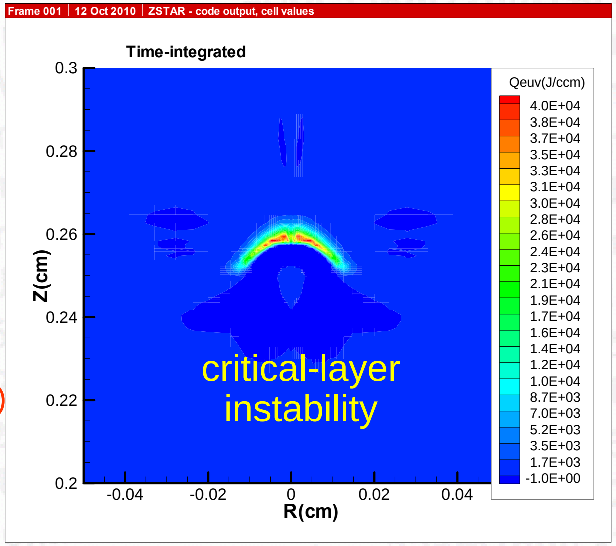
EUV Emission under CO_2- laser pulse

plasma electron temperature T_e





Time-integrated EUV source image (cross-section)



Calculated EUV brightness is up to 12 W/mm² sr kHz

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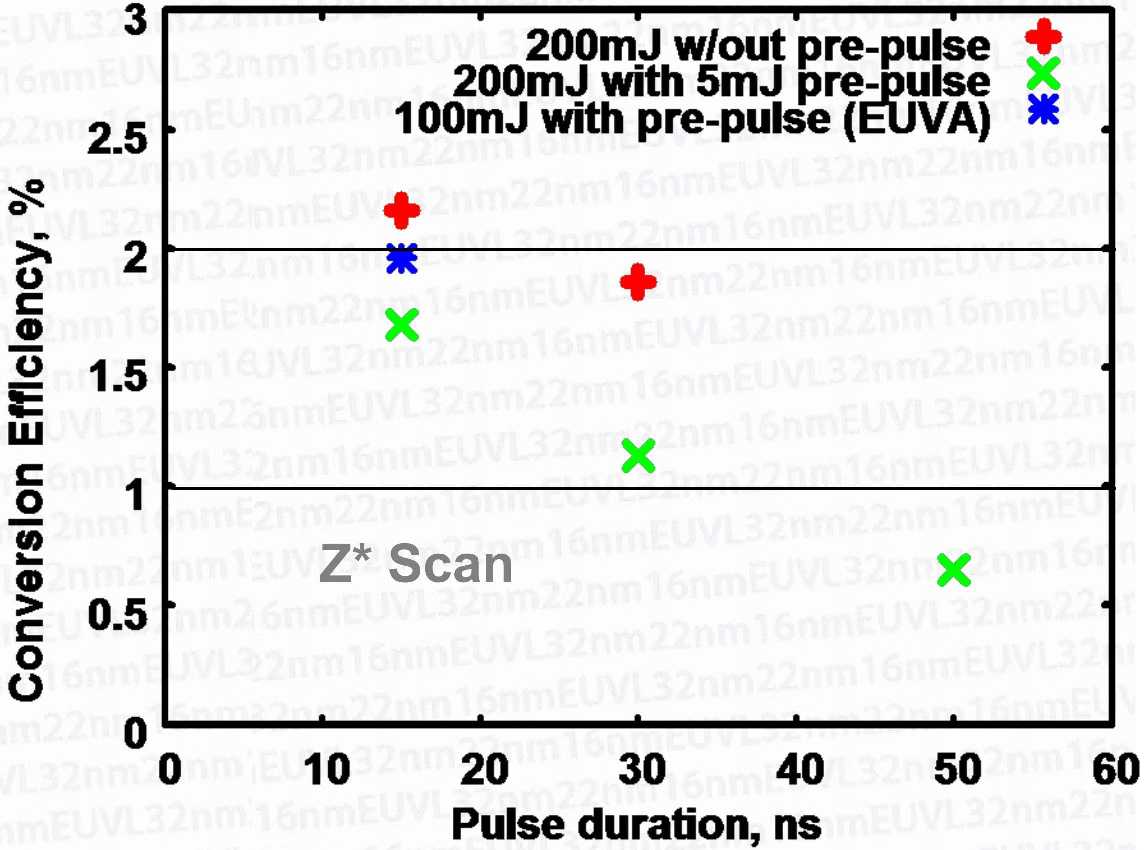
Conversion Efficiency of CO_2-laser

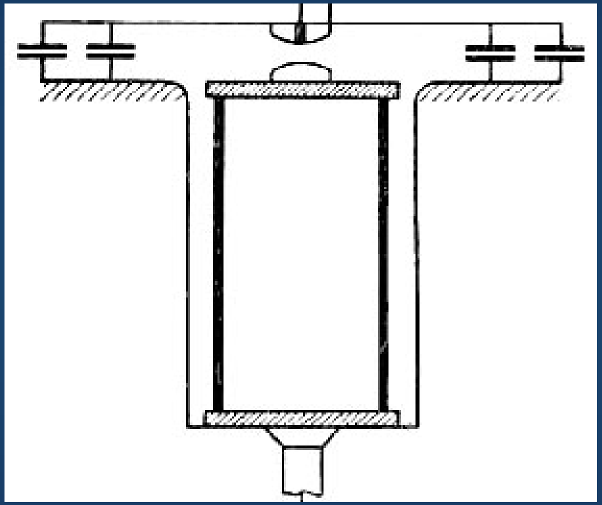
on pulse duration, with & w/out pre-pulse

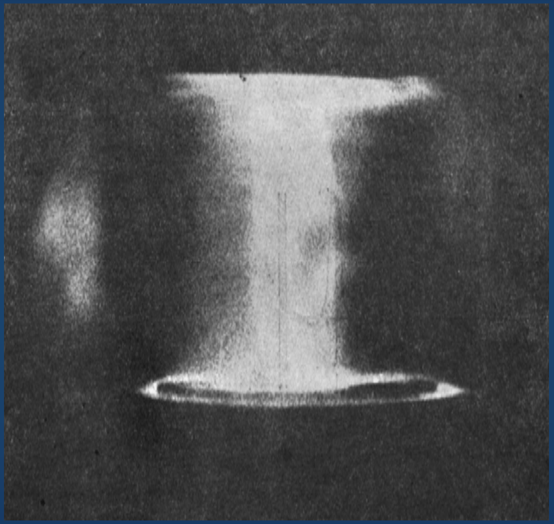
Main pulse: CO_2-laser 0.2 J/pulse, 15, 30 and 50ns fwhm, 200μm focal spot size
Pre-pulse laser (if applied): Nd:YAG 5 mJ/pulse, 10ns fwhm, 40μm spot size

Target:
40μm diameter
tin droplet for 200mJ
laser energy
or
20 μm for 100mJ



Z-pinches





Bennet condition

$$NT = I^2 / 2c^2 (1+\bar{Z})$$

Pease-Braginskii limit

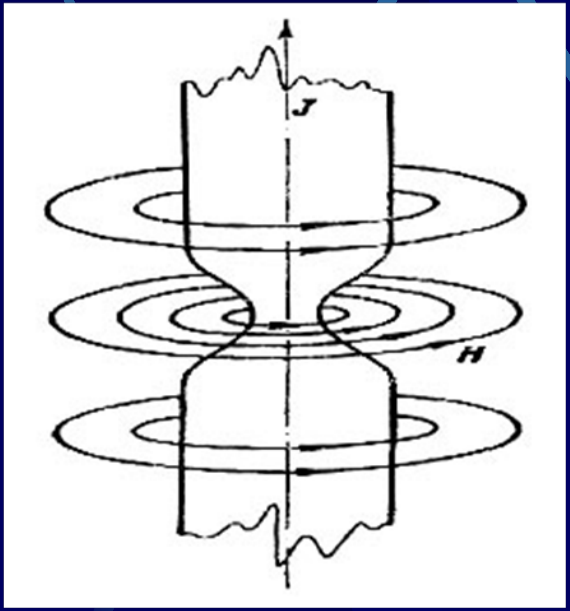
$$T_{\max} = I_{PB}^2 / 2c^2 N (1+\bar{Z})$$

$$I_{PB} = 1.6 MA$$

Igor Kurchatov presentation at Harwell (UK) opened Z-pinches for international collaboration (1956)

MHD Instabilities were Discovered in 1953

The singularity appears on current traces (Leontovitch, Osovets)



Mode m=0

$$\rho \frac{d^2 \delta r}{dt^2} = \delta r \, I^2 / \pi c^2 r^3$$

$$t^{-1} = c_A / r$$

Exist also higher modes m= 1, 2,…

In radiative Z-pinches, a plasma slippage modifies the instability development

Fundamental Understanding

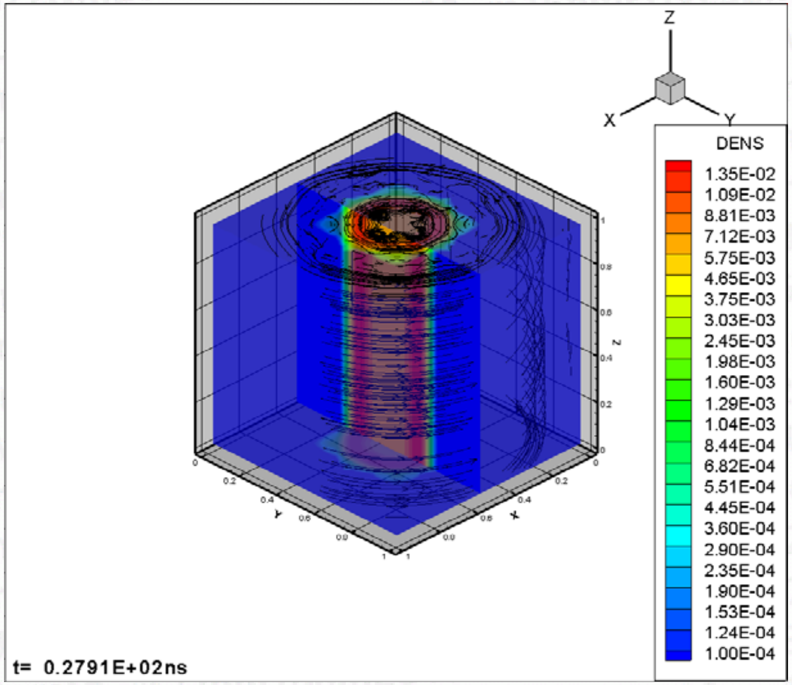
Z* MHD code: 3D modeling of Z-pinch

What can happen with a high current Z-pinch at the end of its life?

Bennet equilibrium impossible due to Pease-Braginskii limit:

Plasma disintegration?
Current disruption?
Anomalous resistivity?

Filamentation of the current on fragments below I_{PB} with generation of B_z; than transformation to a force-free $\vec{j} \parallel \vec{B}$ configuration ?



5MA through tungsten plasma

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