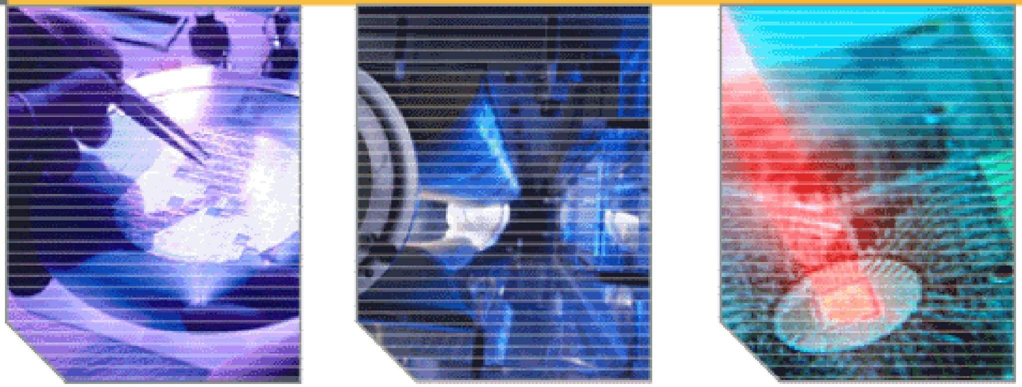
CYMER®

Performance and Scaling of a Dense Plasma Focus Light Source for EUV Lithography



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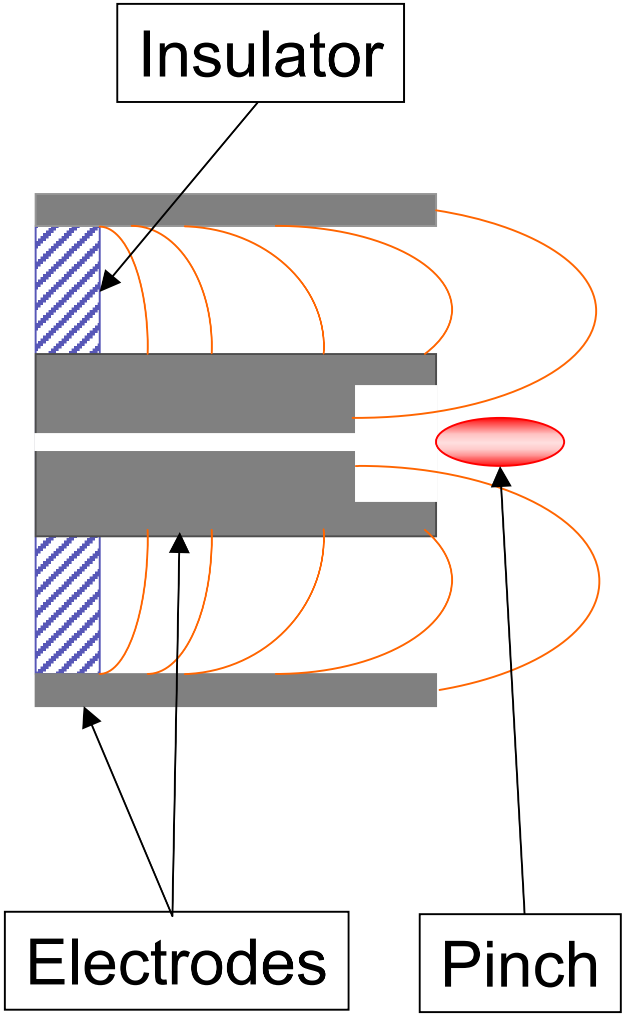
Richard Ness, Oleh Khodykin, Curtis Rettig, Jerzy Hoffman

Presentation Outline

- Overview of Cymer’s EUV source and Development
- EUV Output Power scaling
  - High repetition rate operation
    - Pulsed power, Gas dynamics
  - Thermal engineering
    - Power loads calibration, modeling
  - EUV conversion efficiency
    - Plasma modeling
- EUV output angular stability
- Summary

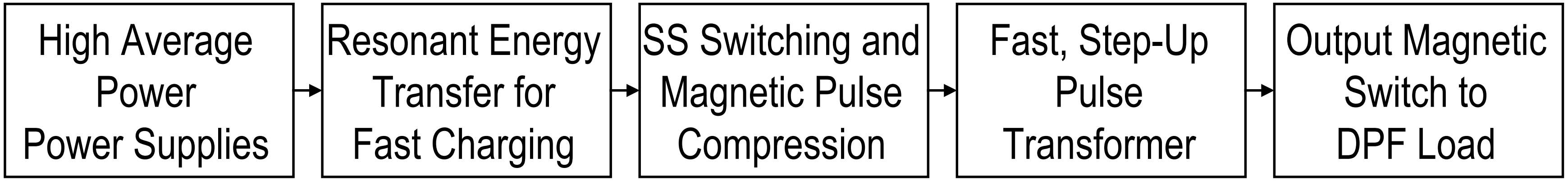
Overview of Cymer’s EUV source and Development

Cymer DPF EUV Source System



- Open source geometry
  - High collection angle (up to 2π steradian)
  - High gas flow, good clearing of discharge zone for high repetition rate operation
- Proven pulse power system
  - Reliable (based on Cymer's DUV excimer laser technology)
  - Scalable to high repetition rates (6–10 kHz)
  - Contains output magnetic switch for reliable high repetition rate
- Source element flexibility
  - Xenon is baseline design
  - DPF will also work with Lithium or Tin

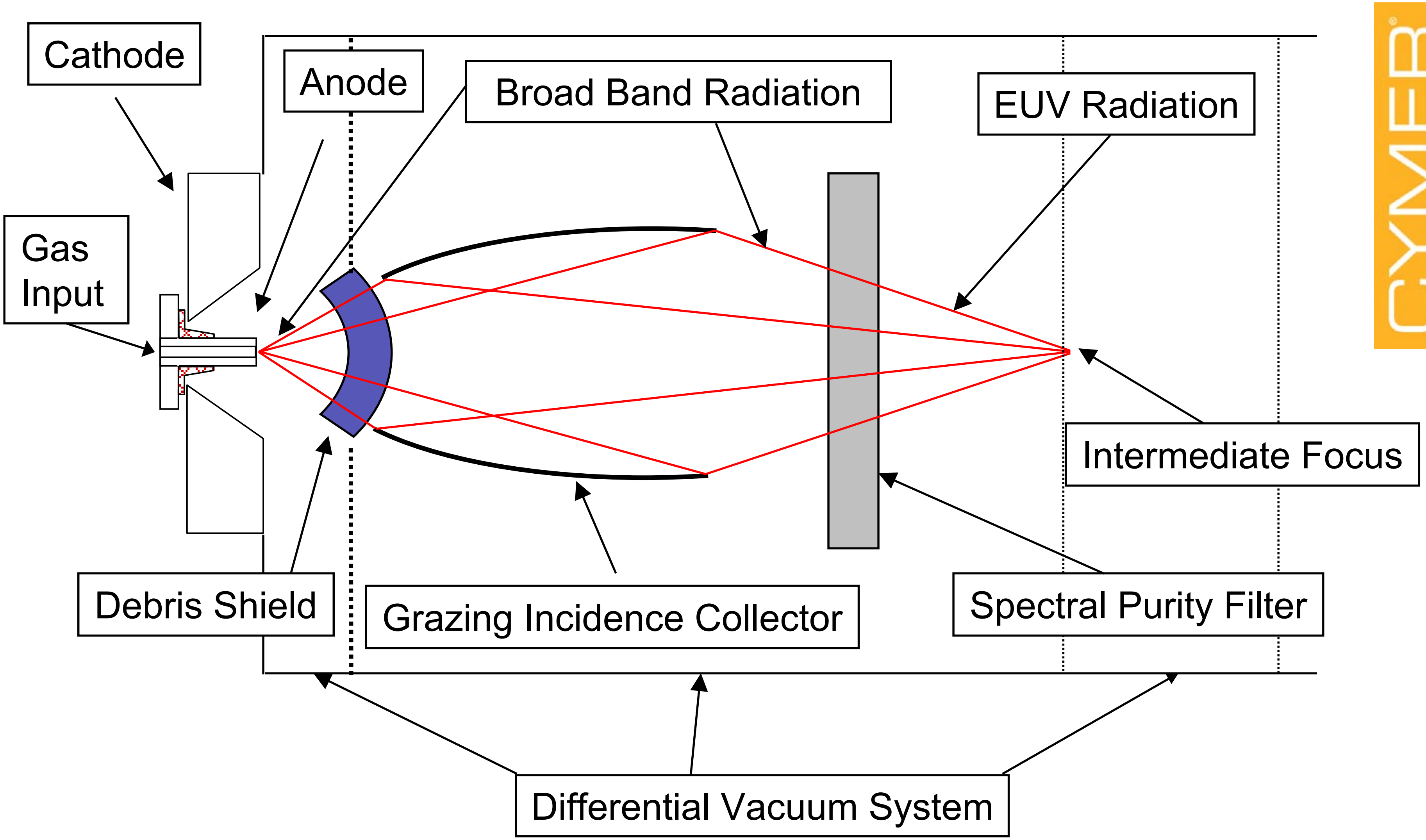
Cymer DPF Power System



High Average Power Power Supplies → Resonant Energy Transfer for Fast Charging → SS Switching and Magnetic Pulse Compression → Fast, Step-Up Pulse Transformer → Output Magnetic Switch to DPF Load

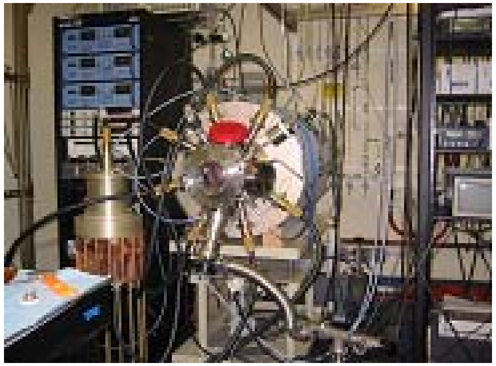
- High Average Power (~30 kW/Module) Power Supplies Provide Initial DC Charging Voltage After Conversion From AC Power Lines
- Resonant Energy Transfer Provides Fast Charging of Pulsed Power System With Tight Regulation to Support High Rep-Rate Operation
- Solid State Switching and Magnetic Pulse Compression Generate Fast Pulses Required by DPF at High Rep-Rates (Up to 10 kHz)
- Fast, Step-Up Pulse Transformer With Low Inductance, Increases Pulse Voltage by 4X While Still Maintaining Fast Risetime
- Output Magnetic Switch Provides Consistent, Reliable Switching of Pulse Energy to DPF Load With Low Inductance, Enabling High Peak Currents and High dI/dt Required for Efficient Pinch Operation

EUV Light Source System

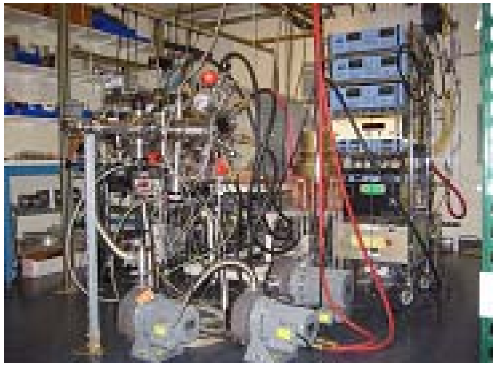


Cymer EUV Prototype Machines

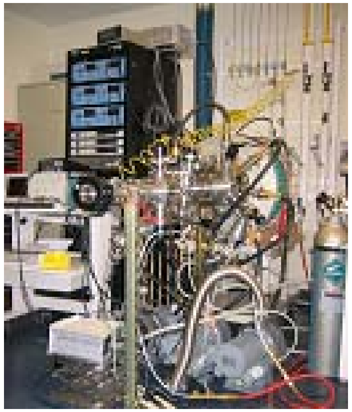
Parallel Development in Key Technology Areas



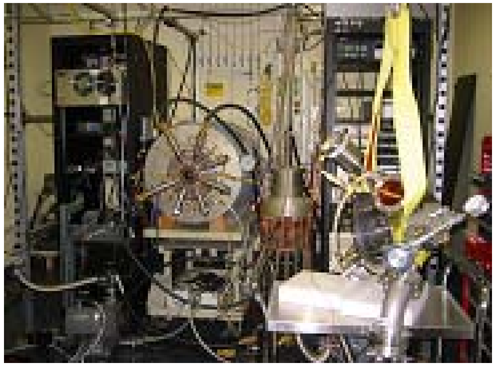
Lifetime & Debris Mitigation



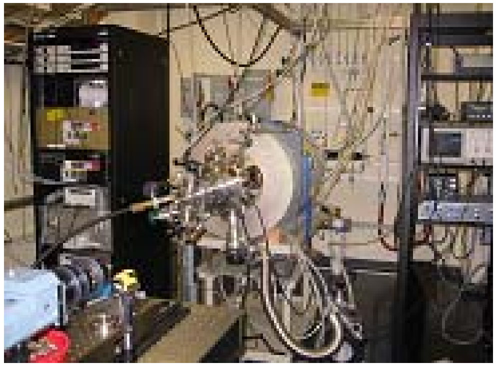
High Rep. Rate Operation



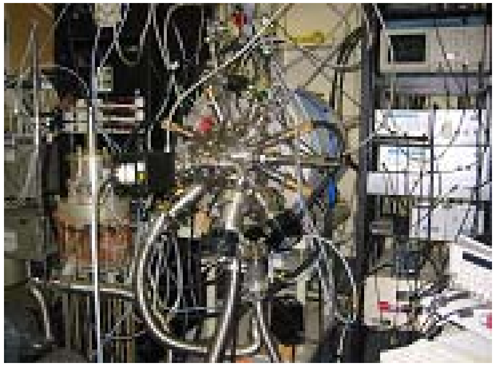
Pulsed Power Development



Power Scaling & Thermal Engineering



Metrology & EUV Optics



Plasma Optimization

EUV Output Power Scaling

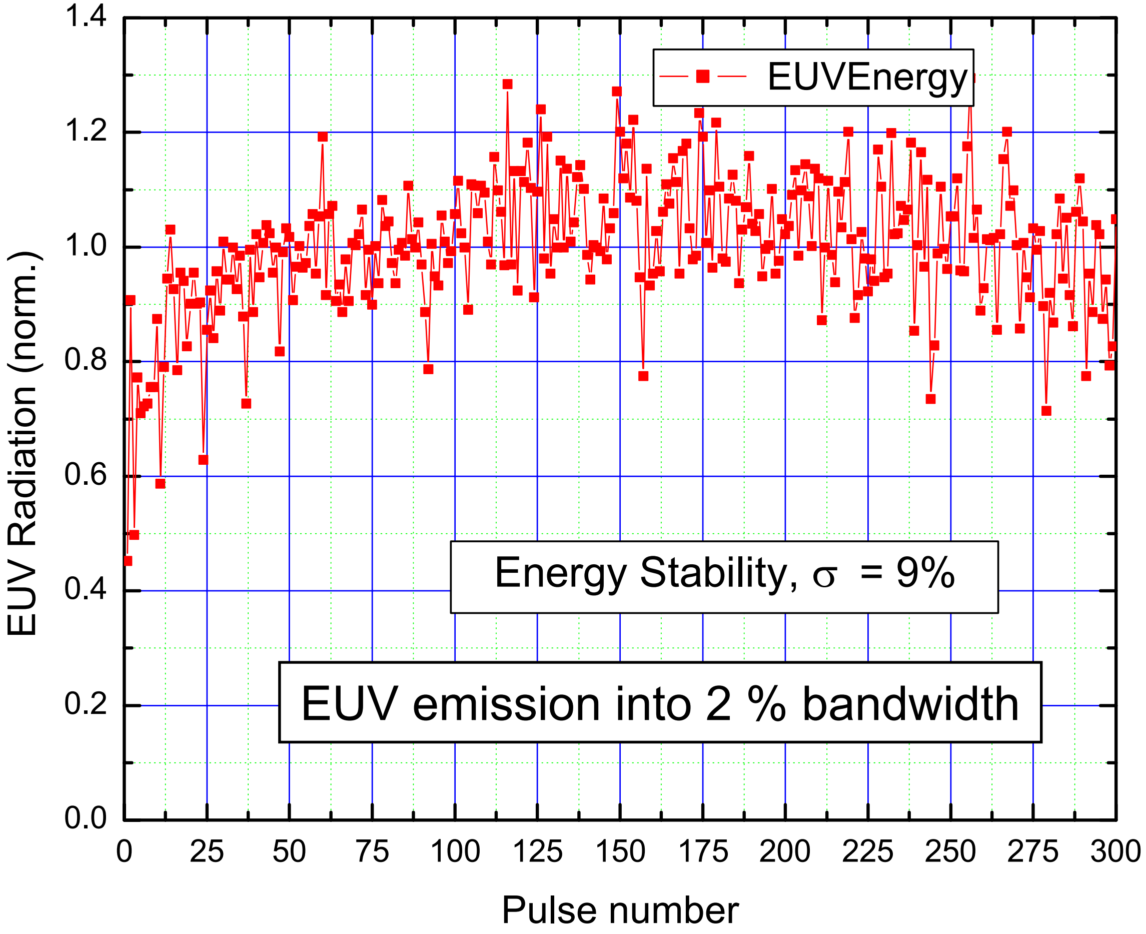
Paths to Higher EUV Output Power

- Output power can be scaled by increasing repetition rate, conversion efficiency and collection efficiency
- Repetition rate can be increased as thermal extraction capability increases
  - Sufficient heat dissipation can be achieved by implementing advanced thermal engineering strategies and optimizing anode geometry.

- Repetition rate scaling to > 6 kHz is not anticipated to be a problem
  - No show stoppers with Cymer pulse power system
  - Gas dynamics at higher repetition rate is not anticipated to be a limitation

- Conversion efficiency may be improved by optimizing plasma conditions and / or using other source elements

Burst Operation at 4 KHz Repetition Rate

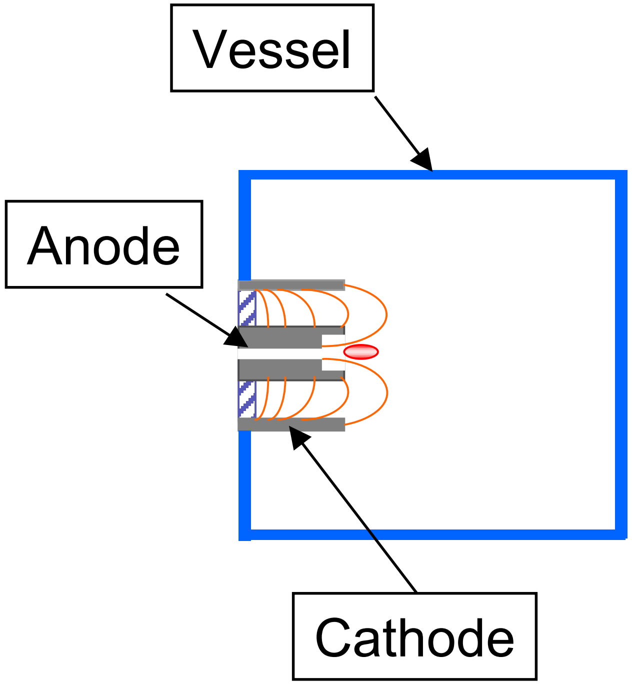


Energy Stability, σ = 9%

EUV emission into 2 % bandwidth

- EUV output depends on gas composition
- Injection geometry affects EUV in band emission efficiency at all repetition rates
- Gas recipe optimization depends on repetition rate

Calorimetry of Water-Cooled DPF at 1 kHz

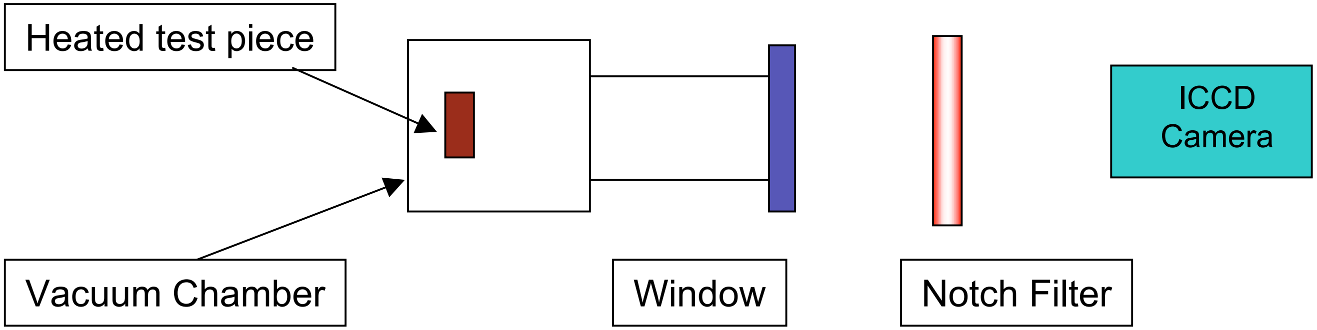


- Open channel water cooling
- 13 kW total power input
- Heat removal distribution
  - Anode - ~50%
  - Cathode - ~40%
  - Vessel - ~10%

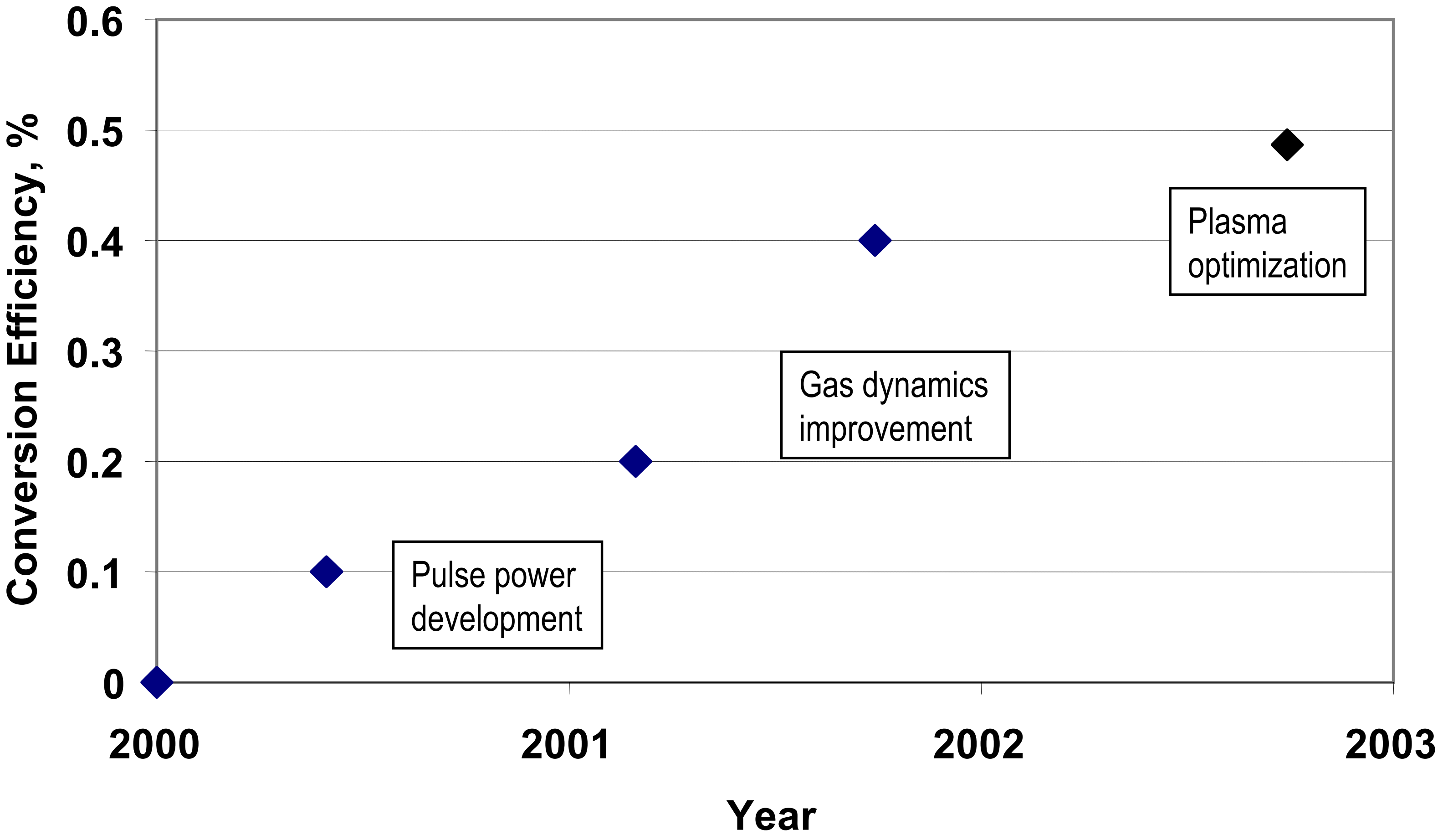
- Porous Media, Water-Cooled Electrodes: expected to extract 2-5 kW/cm^2

Measurement of the Thermal Load of DPF Electrodes

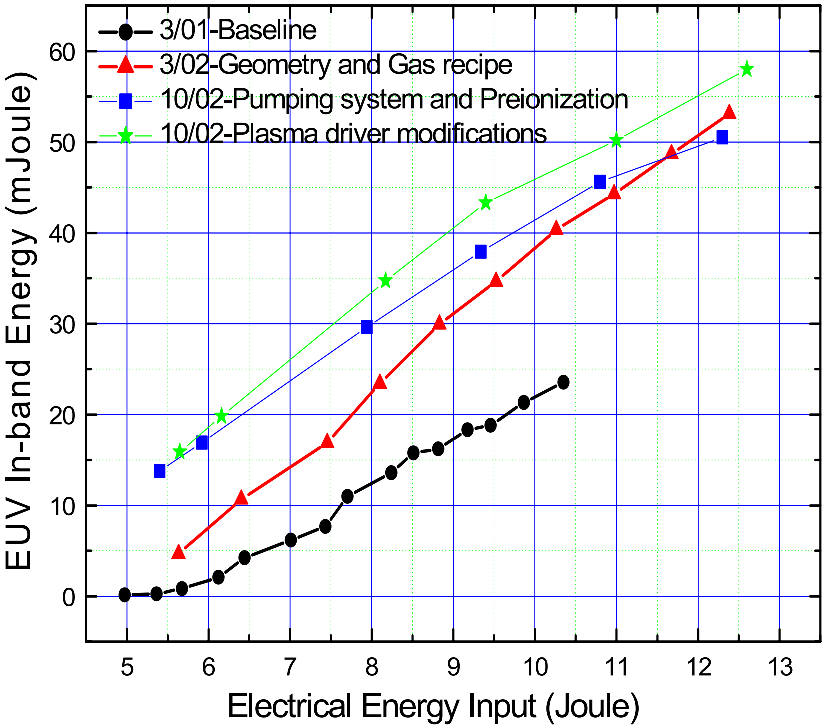
- Goal:
  - Thermal data as input for the thermal modeling of the DPF.
  - Time-resolved temperature measurements.
  - The accuracy of the thermal measurements are verified by calorimetry.
- Method:
  - Calibration of a gated ICCD camera using a test stand with electrode material heated to high temperatures.
  - Temperature is measured with thermocouples.

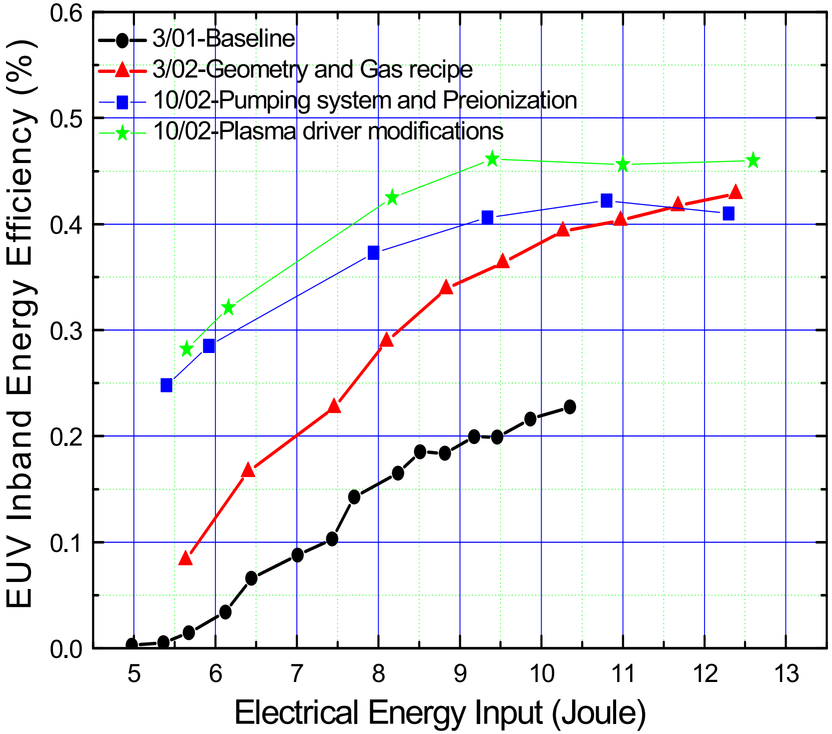


Progress on EUV Conversion Efficiency



In Band EUV Energy and Efficiency

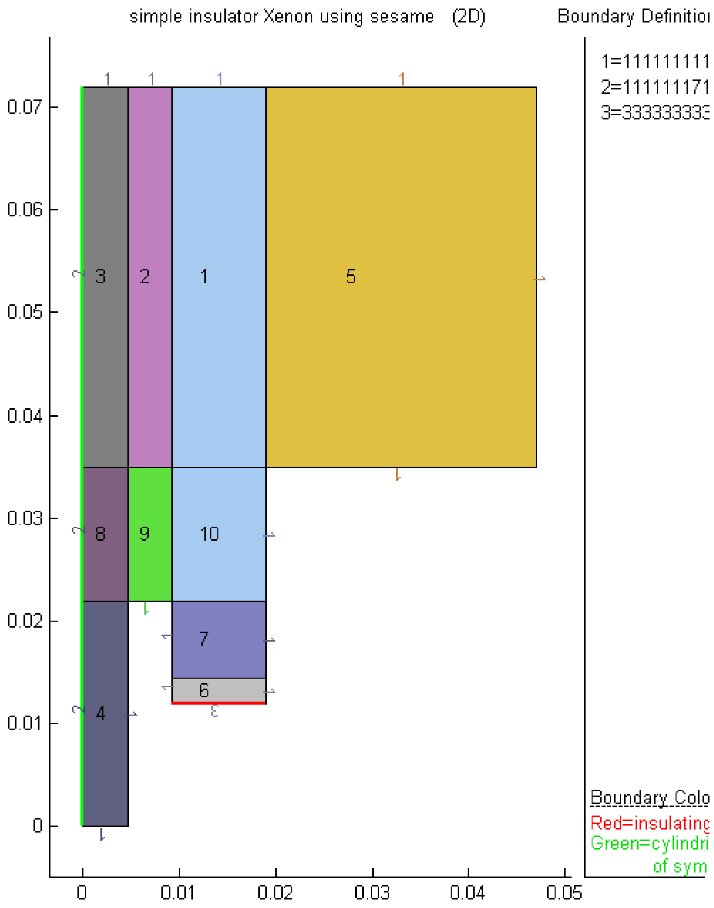




Demonstrated ~ 55 mJ per pulse (2 π sr, 2% bandwidth at 13.5 nm).

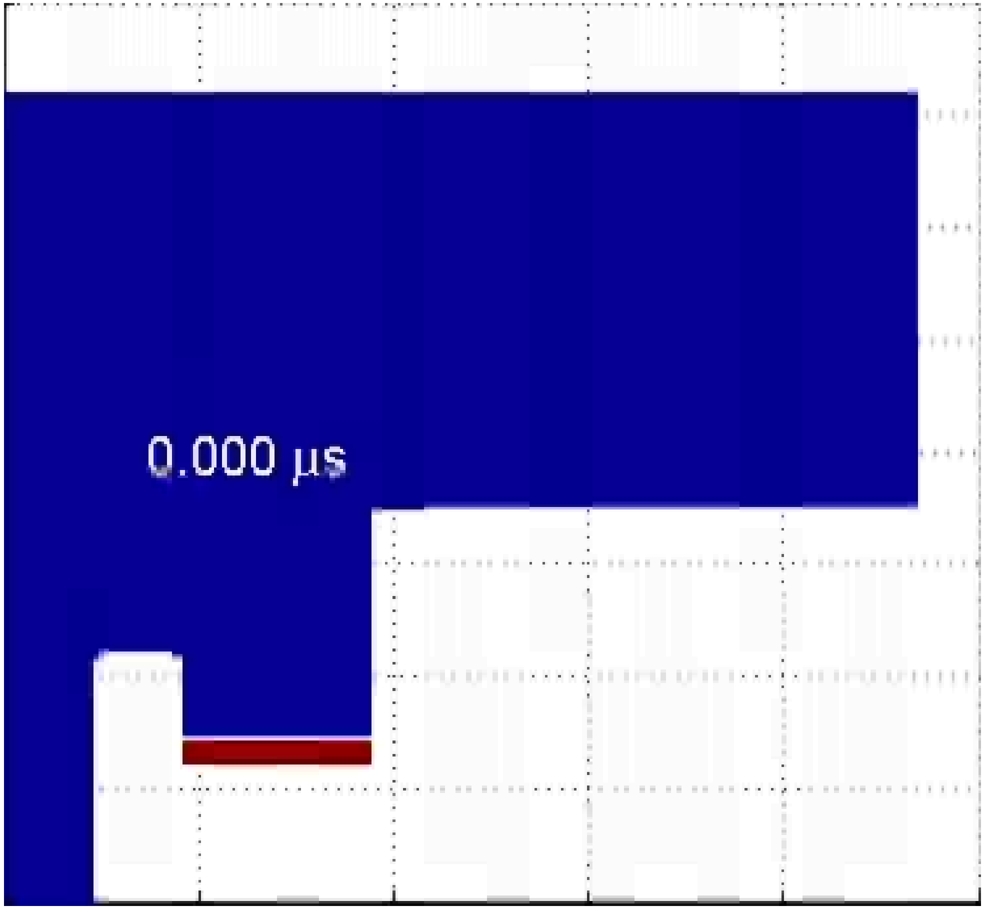
Increased efficiency at low input energy.

MHD Plasma Simulation of Pinch Dynamics



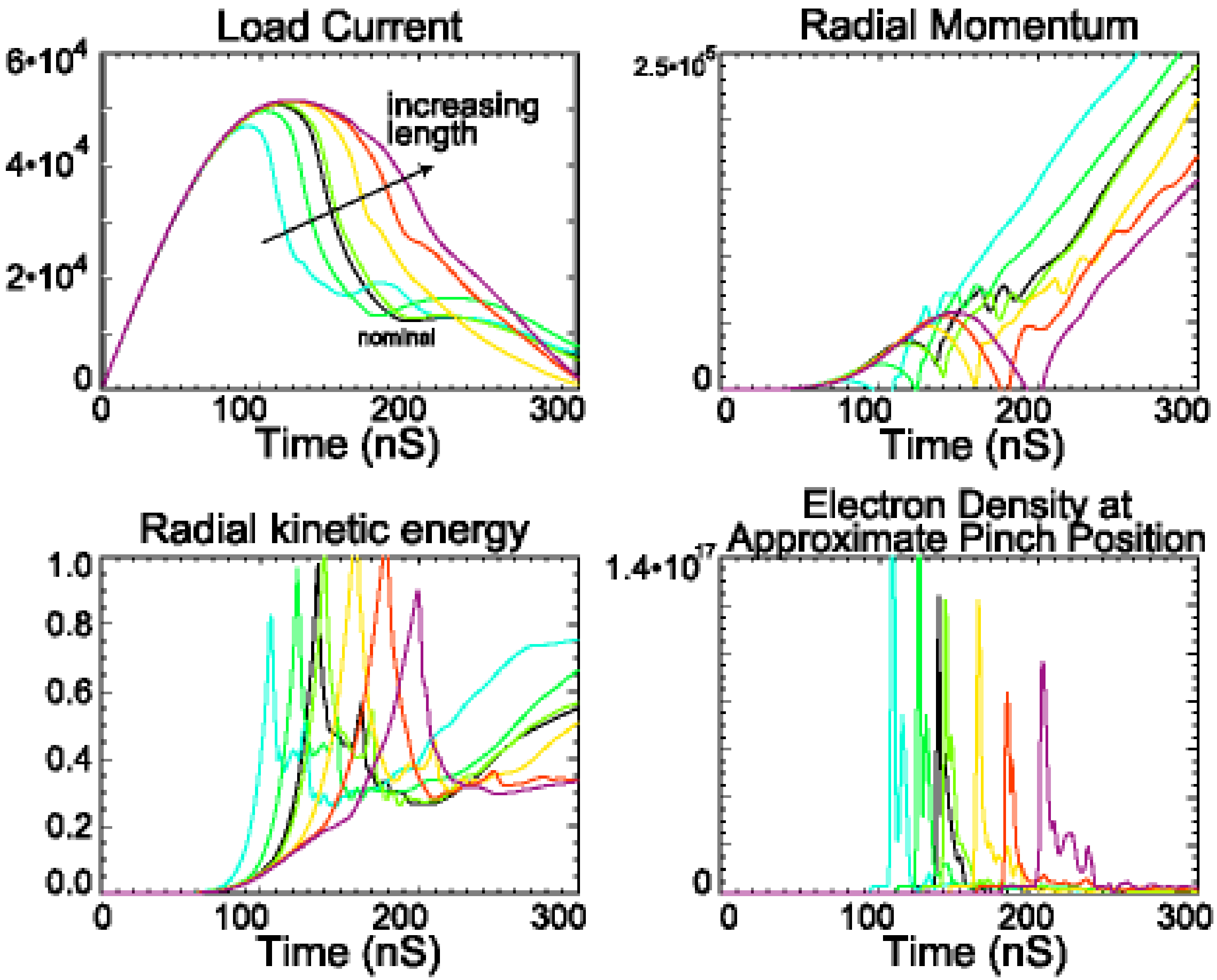
- The 2D MHD code “MHRDR”, developed by I. Lindemuth and P. Sheehey of LANL and ported to UNR, has been adapted to more specific low energy dense plasma focus geometry. (B.S. Bauer talk, session 4)
- Plasma fluid equations are coupled self-consistently to an electrical circuit model in 2D axis-symmetric geometry.
- LANL SESAME atomic database is used to compute: the equation of state, ionization level, radiative energy loss, and resistivity.

Simulation of General DPF Dynamics



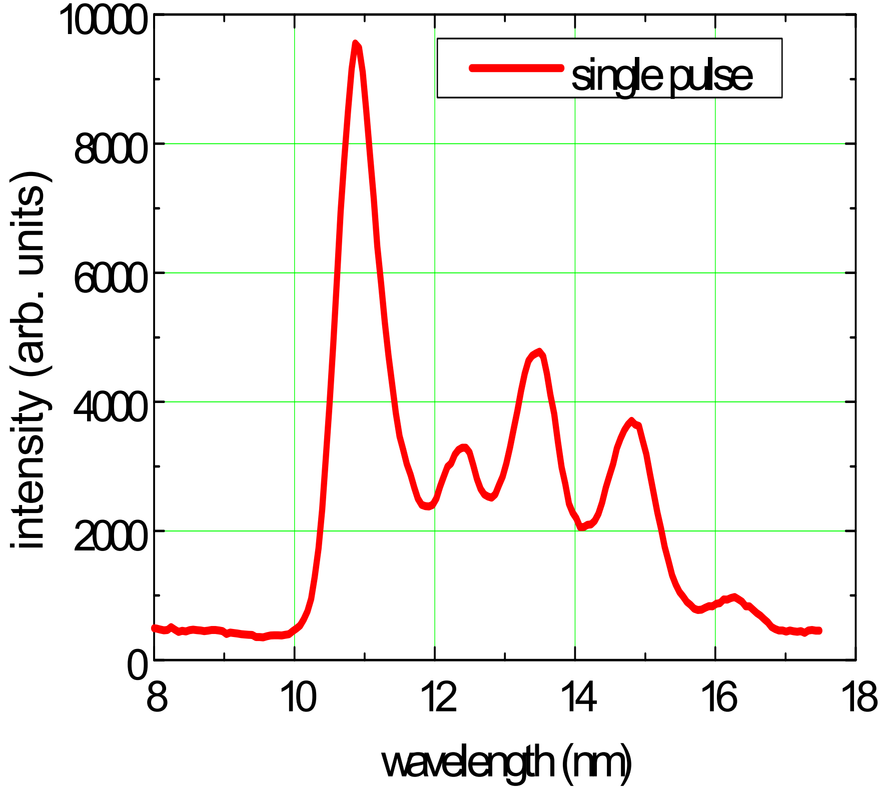
- Evolution of plasma pressure during axial rundown and pinch phases.

Simulation for Geometry Optimization

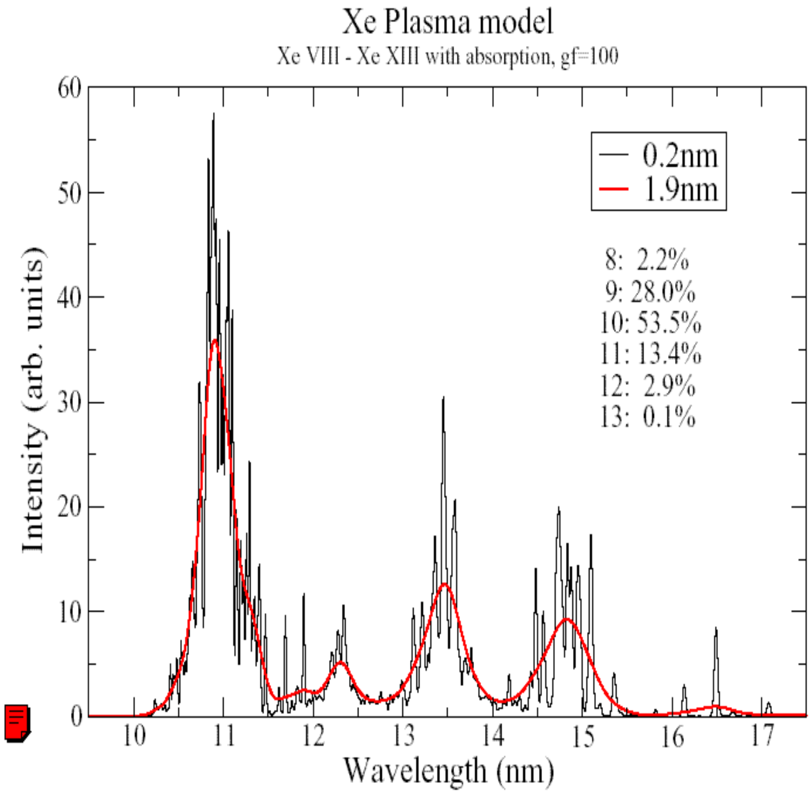


- Existence of optimum is consistent with experiments.

Comparison of Spectra: Calculation and Experiment



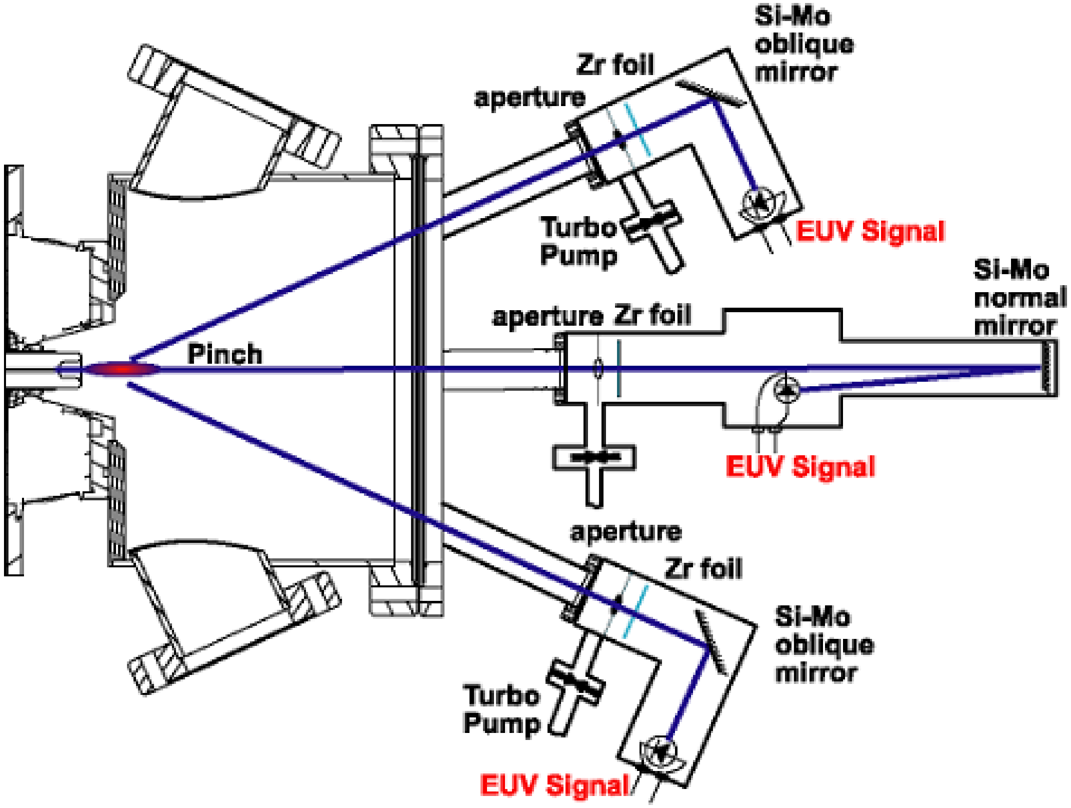
Measured transmission grating spectrum



Hartree-Fock calculation by Dr. M.Martins

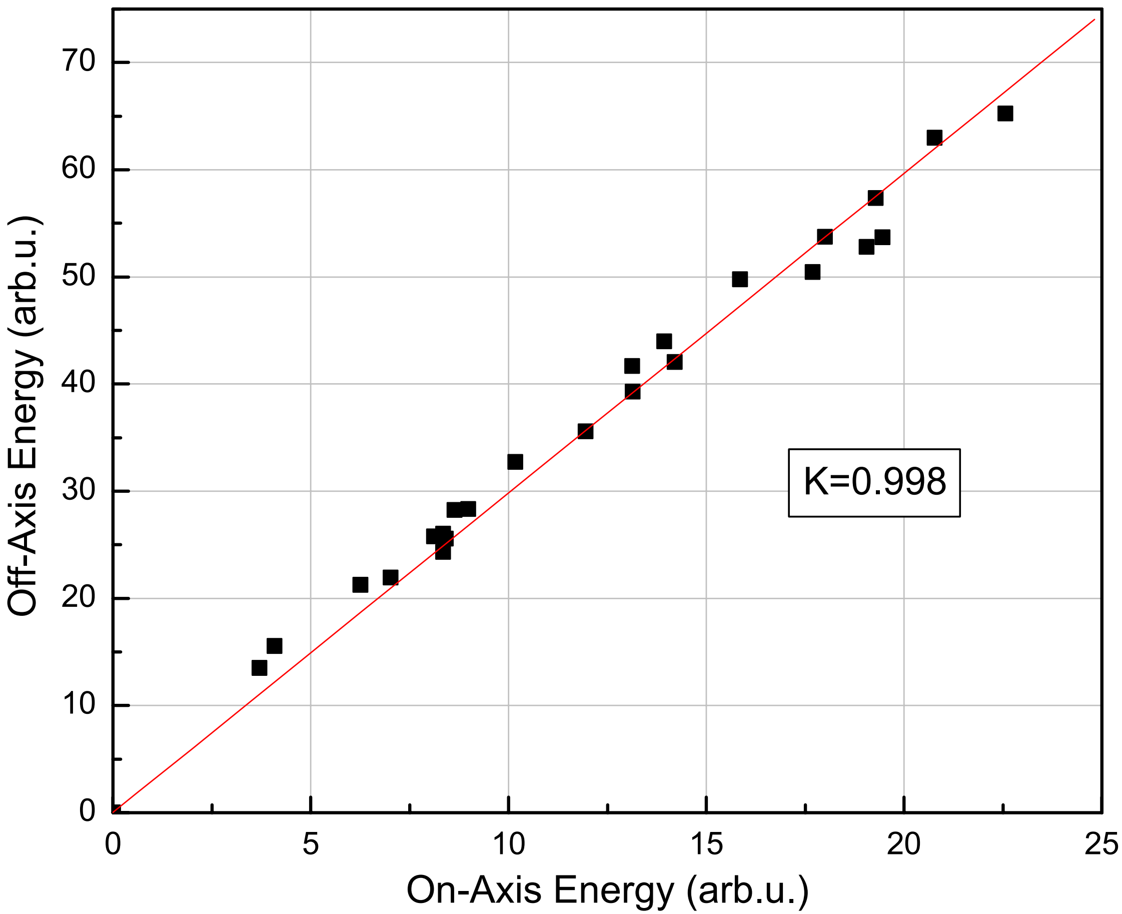
EUV Output Angular Stability

On-Off Axis EUV Energy Measurement Setup



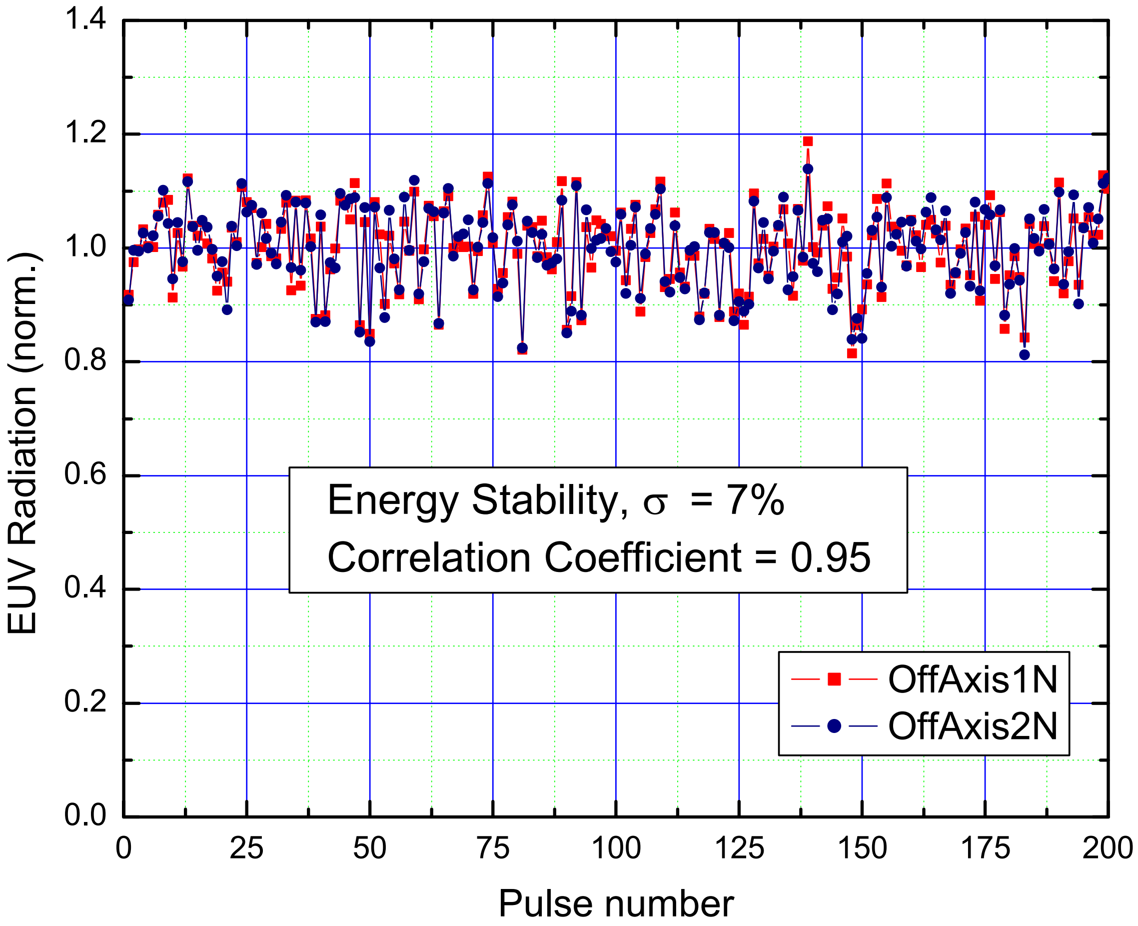
- EUV energy measured on-axis and at 22.5 degrees off-axis
- Filtering accomplished by Zr foil and Si-Mo 45 degree mirror

On / Off-Axis EUV Energy Measurements



- EUV energy measured on-axis and at 22.5 degrees off-axis.

Off-Axis EUV Energy Pulse-to-Pulse Correlation



- EUV output at different angles has high correlation.

Current Source Performance

EUV efficiency with Xe, (2% BW, 2π sr)	> 0.45%
EUV energy per pulse (2% BW, 2π sr)	~ 55 mJ
Average source size (FWHM)	~ 0.4 x 2.5 mm
Source position stability (centroid)	< 0.05 mm, rms
Continuous repetition rate	1000 Hz
Burst repetition rate	4000 Hz
Energy Stability	~ 7 %, rms
Avg. EUV Output Power (2% BW, 2π sr)	50 Watt
EUV Output Power, Burst (2% BW, 2π sr)	200 Watt

EUV Power

	Today	Future	Required
Steady State Mode			
Thermal Extraction Power (W)	11000	50000	100000
Conversion Eff.	0.45%	0.60%	0.70%
EUV Power (W), 2% bw,2π sr	50	300	700
Collection Efficiency	20%	30%	30%
Collected EUV (W)	10	90	210
Collector Trans.	70%	70%	70%
Debris Mitigation	80%	80%	80%
SPF	100%	100%	100%
Gas Trans.	90%	90%	90%
EUV at Interm. Focus (W)	5.0	45.4	105.8

Cymer DPF Source Technology Roadmap

Metrics	Oct-00	Mar-01	Oct-01	Mar-02	Oct-02	Mar-03	Mar-04	Mar-05	Mar-06	Mar-07
Central Wavelength (nm)	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
In-band power, 2%BW, 2π sr, (W) • Average, continuous • In-burst maximum (@ rep rate)		1 20	4 40	8 80	27 108	50 200	100 300	180 480	240 480	380 630
Available collection angle (sr)	2π available (1.8 used with present collector design, π the future)									
Source emission volume, diam. x length (mm x mm)		0.25 x 1.7	0.25 x 1.7	0.25 x 1.7	0.35 x 2.0	0.4 x 2.5	0.4 x 2.5	0.4 x 2.5	0.4 x 2.5	0.4 x 2.5
Etendue (mm^2•sr)		2	2	3	3	3	3	5	7	7
Demo'd max rep. rate (kHz)		1	1	2	2	4	6	8	8	10
Demo'd contin. rep. rate (kHz)		0.05	0.1	0.20	0.50	1	2	3	4	6
Steady state power dissipation (kW)		0.5	1	2	6	10	20	30	40	60
Source-facing condenser life (pulses to 10% reflectance loss)		>0.5M	>5M	>50M	>50M	>50M	1B	10B	50B	100B
Pulse-pulse spatial stab (μm 3σ)		>250	>250	>250	150	150	100	80	60	50
Pulse-pulse intensity stab. (3σ) Dose stability		27% 2%	27% 2%	27% 2%	21% 2%	20% 2%	15% 1%	10% 0.7%	6% 0.5%	4% 0.3%
Pulse-pulse angular stab. (3σ)	isotropic									
Pulse-pulse pointing stab. (3σ)	isotropic									
Key risk areas		thermal, debris	thermal, debris	thermal, debris	thermal, debris	thermal, debris	thermal, debris	power, lifetime	power, lifetime	power, lifetime
Critical comp. lifetime (pulses)		1M	1M	2M	10M	10M	50M	100M	1B	10B

Summary

- The DPF configuration shows promise for reaching production requirements of an EUV source.
- Demonstrated continuous improvement in Xe conversion efficiency.
- Burst mode operation at 4 KHz does not show any problems with gas dynamics or pulsed power limitations.
- Continued work in thermal management is key to higher power output.
- Source stability is continuously improving.

- Remaining challenges: thermal engineering, debris mitigation, EUV emission and source position stability.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