EUVL Capillary Discharge Source

Status:

Achieves 9W EUV in 2% BW, π sr at 1 kHz
5×10^6 pulse run at 500 Hz reveals no diameter change in capillary
High-mass-flow (760 Torr-l/sec) gas curtain test facility constructed

Advantages:

Direct and efficient electric discharge EUV production
Simple and compact footprint
Scalable to multi-kHz operation
Low Xe pressure at source output region
Etendu well-matched to β-machine requirements
Pulse-on-demand

Challenges:

Capillary erosion and required replacement
Debris mitigation required to eliminate condenser contamination
Materials experience high temperatures in vacuum environment

Supported by EUV, LLC and International Sematech under LITH 114

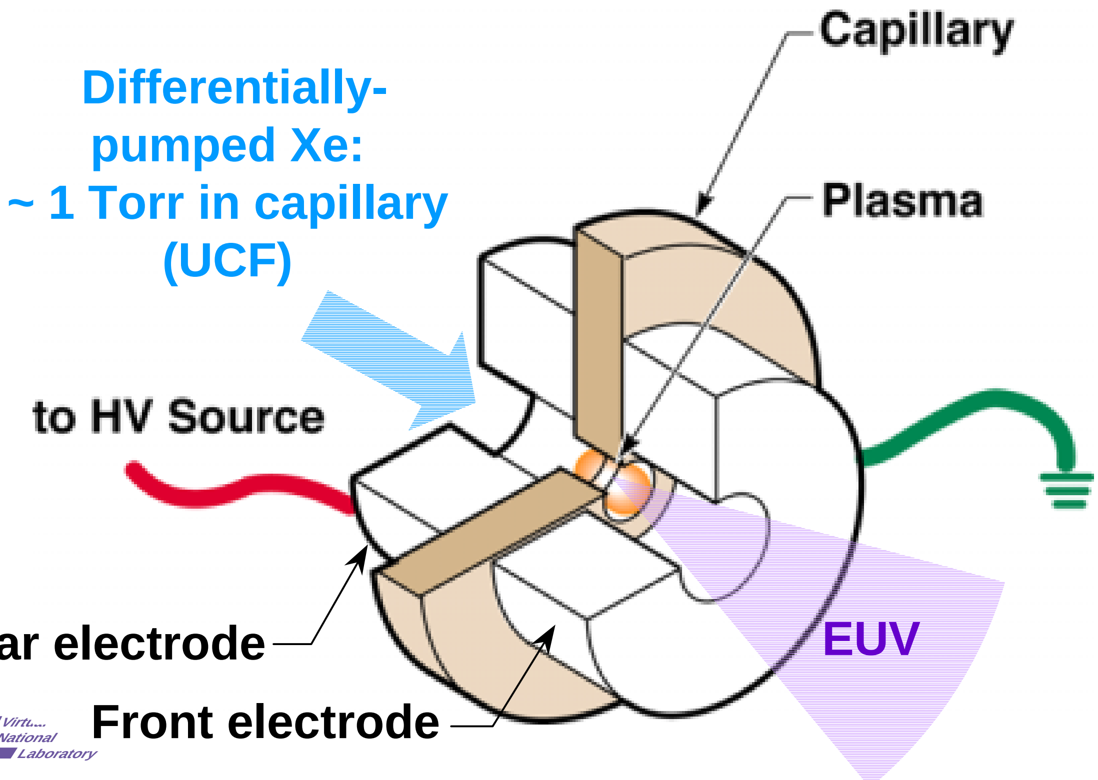
Discharge Source Development Team

- Sandia National Labs
  - Howard Bender, Dean Buchenauer, Neal Fornaciari, Mike Kanouff, Steve Karim, Chris Moen, Ken Stewart
- University of Central Florida
  - Bill Silfvast, Greg Shimkaveg
- TRW
  - Steve Fornaca, Harry Shields

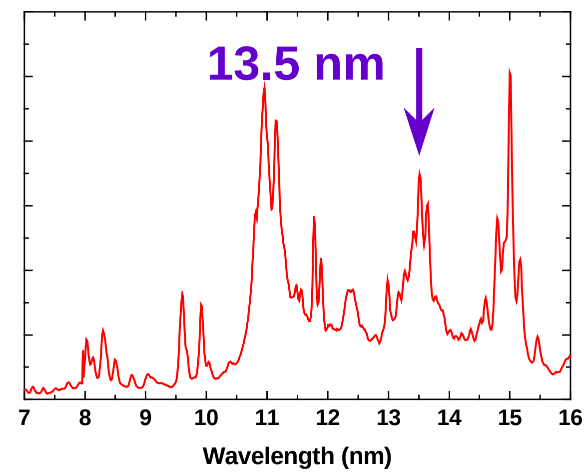
- Funding
  - International SEMATECH, EUV/LLC

Capillary Discharge Source Overview

Approach
- Concept originated by Silfvast & Klosner/UCF
- Direct electrical ➡ EUV energy conversion
- 1 kHz, 14 W source in development
- 5 kHz, >50 W source needed for β-tools
- Lifetime improvements being developed

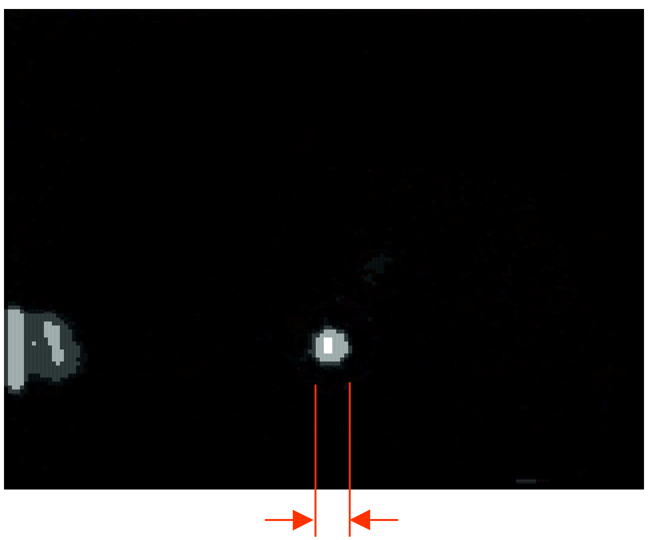


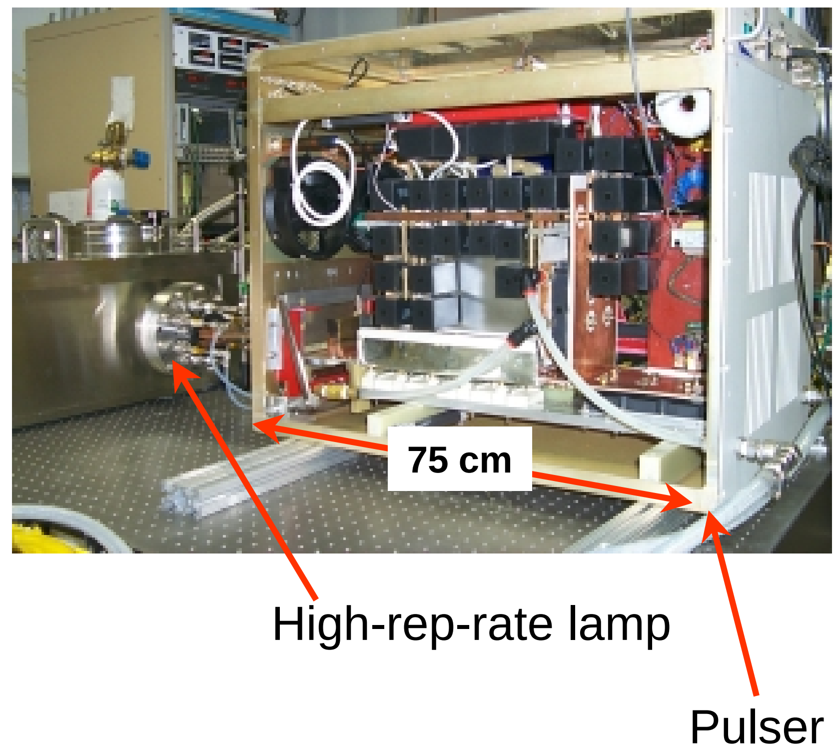
EUV Output Spectrum



14 W Power scale-up in progress

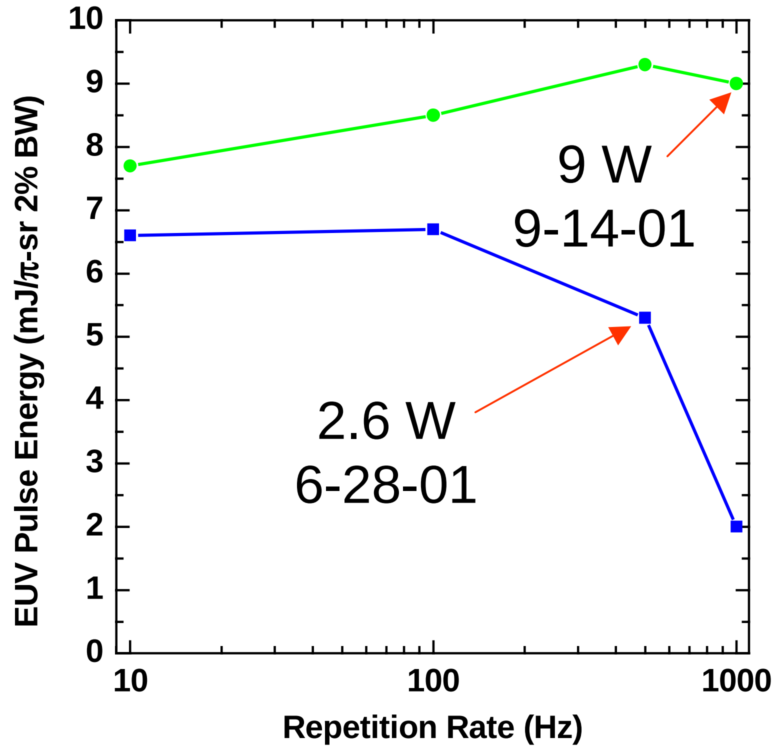
- Repetition rates up to 1.5 kHz
- 5000 A output at 1500 V
- Pulse durations from 0.5 to 4 μs
- Pulsed and Simmer pre-ionization for improved stability and reduced lamp erosion





Improved operational parameters increase in-band EUV power generation from 2.6 to 9 W

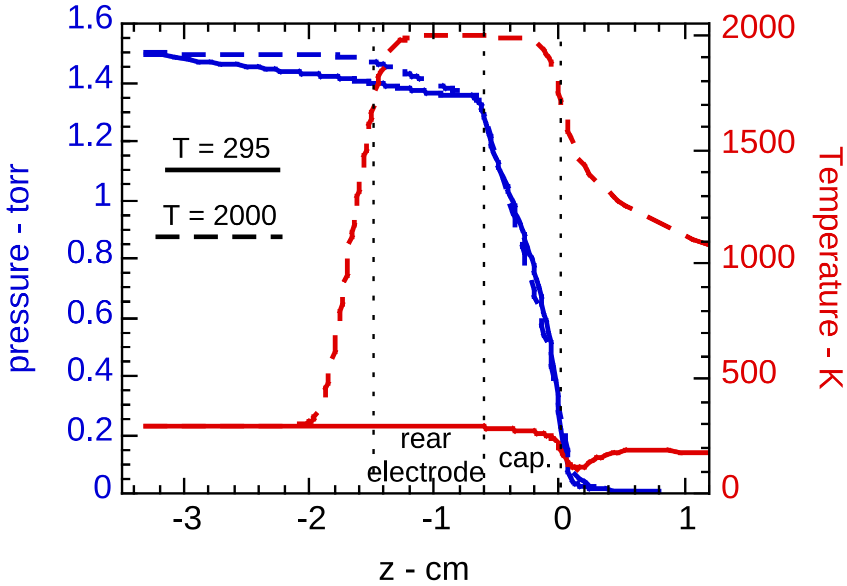
- Operating Conditions
  - Average of 25 pulses from 300 pulse burst
  - Increased Xe pressure and flow rate
  - 2 μs pulse width (up from 1.7)
  - Pulsed pre-ionization used
  - Improved electrode processing reduced arcing
  - Equivalent conversion efficiency of 0.15% in π sr

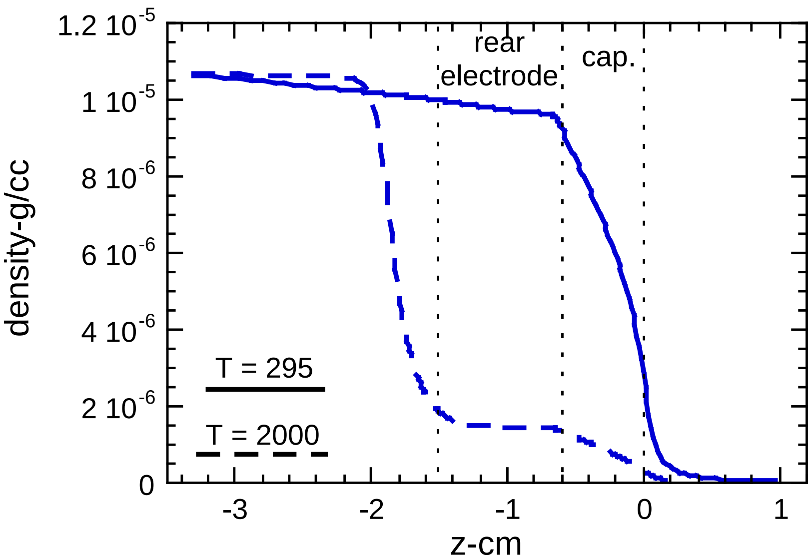


Power shown is integrated over measured 0 - 60° angular distribution

Steady-state calculations show an 8x decrease in Xe density with the capillary bore temperature at 2000 K

Xenon source pressure = 1.5 torr



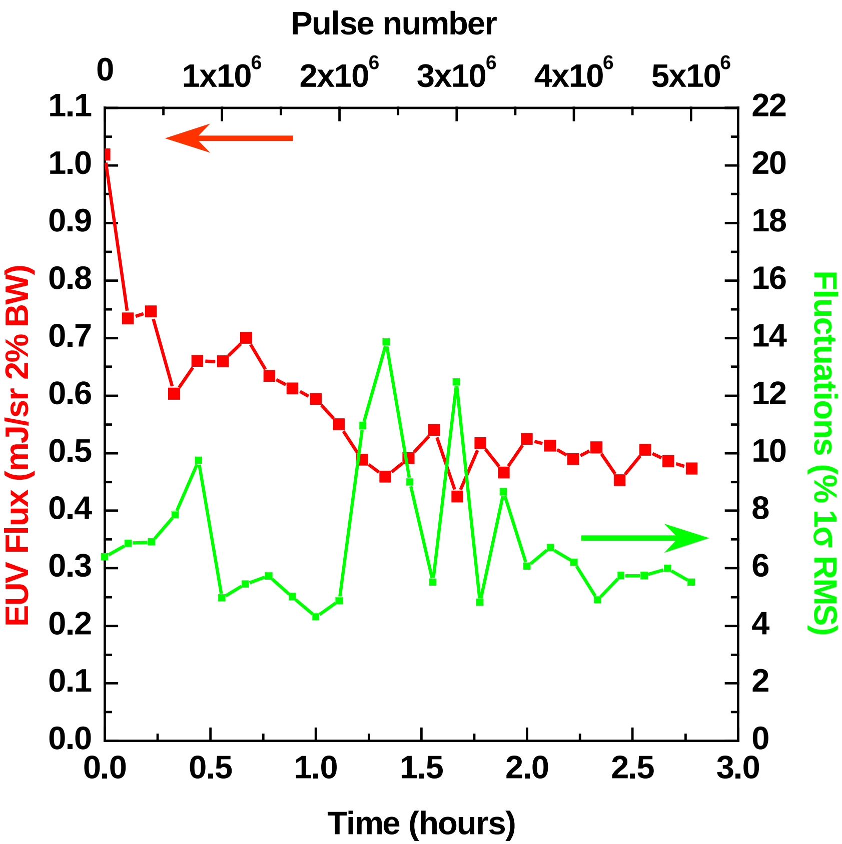


capillary temperature (K)	density at cap. center (mg/cc)	xenon flow rate (mg/s)
295	0.0069	0.588
2000	0.00089	0.0707

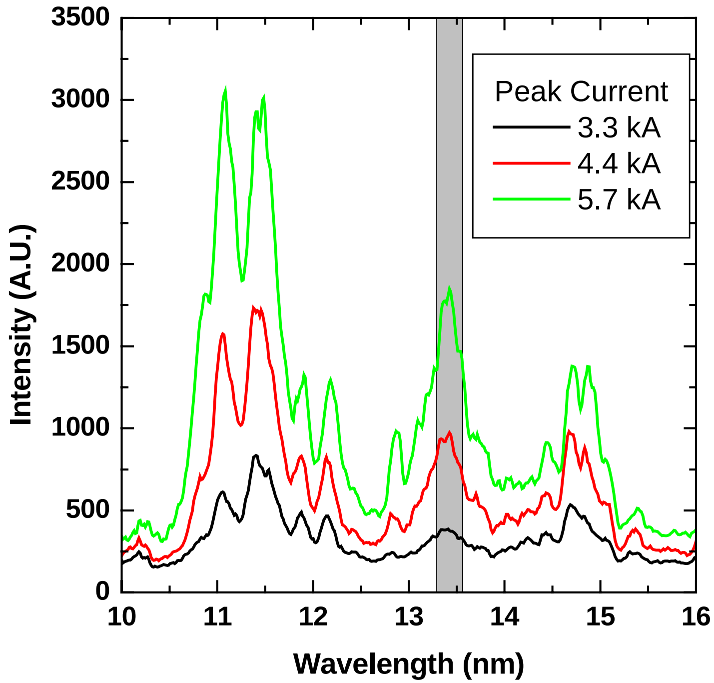
Stability characterized over 5 million pulse operation

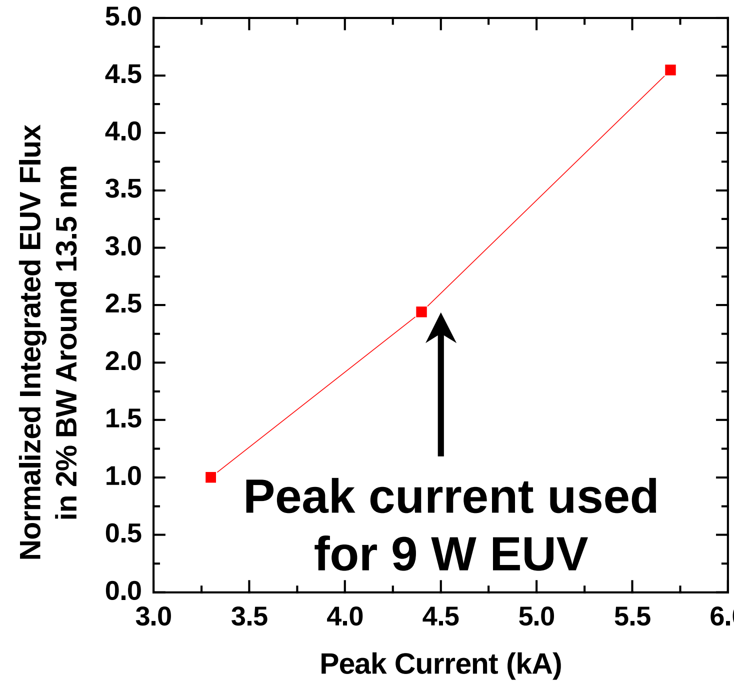
Lamp designed for steady-state operation at 1.5 kW applied power

- **Average applied lamp power: ~1.5 kW**
- **No increase in capillary diameter measured**
- **No active power stabilization applied**
- **Fluctuations increased in middle of run due to preionization instabilities**
- **Peak current: 3.2 kA**



Spectral measurements show significant increase in EUV flux with peak current



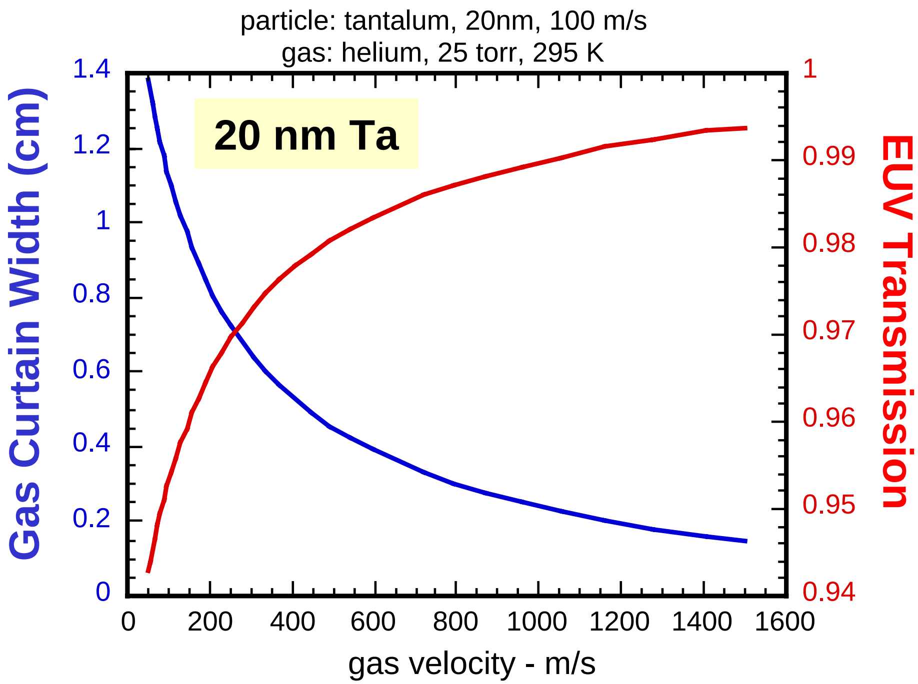


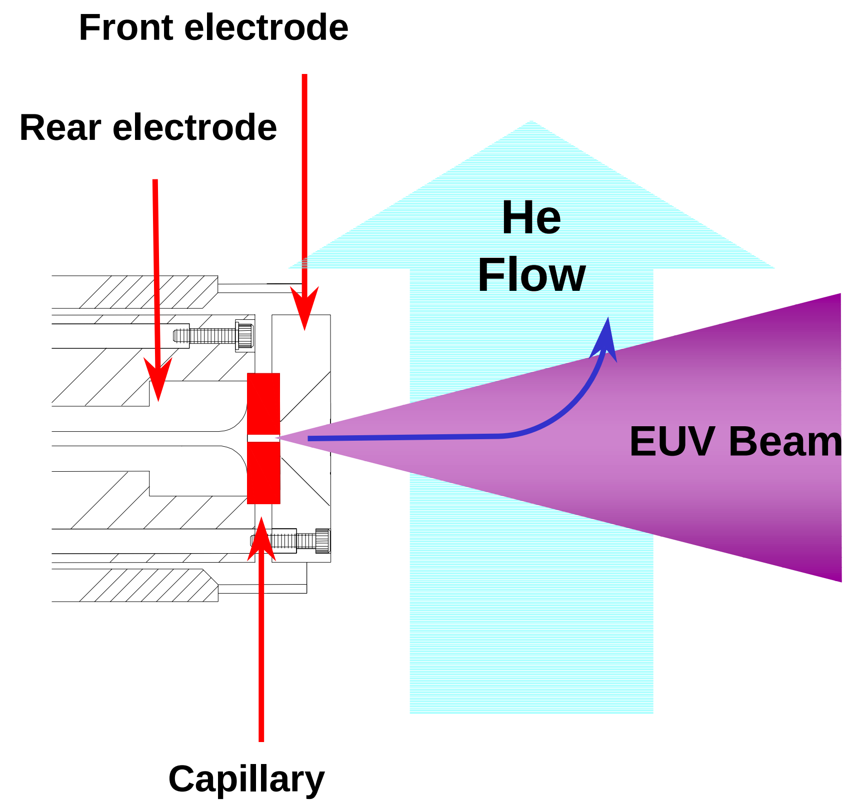
Spectral data as function of peak current (bipolar pulse)

Integration of the spectra in 2% BW shows EUV flux increase of 1.5 per kA

Gas curtain developed to block lamp debris

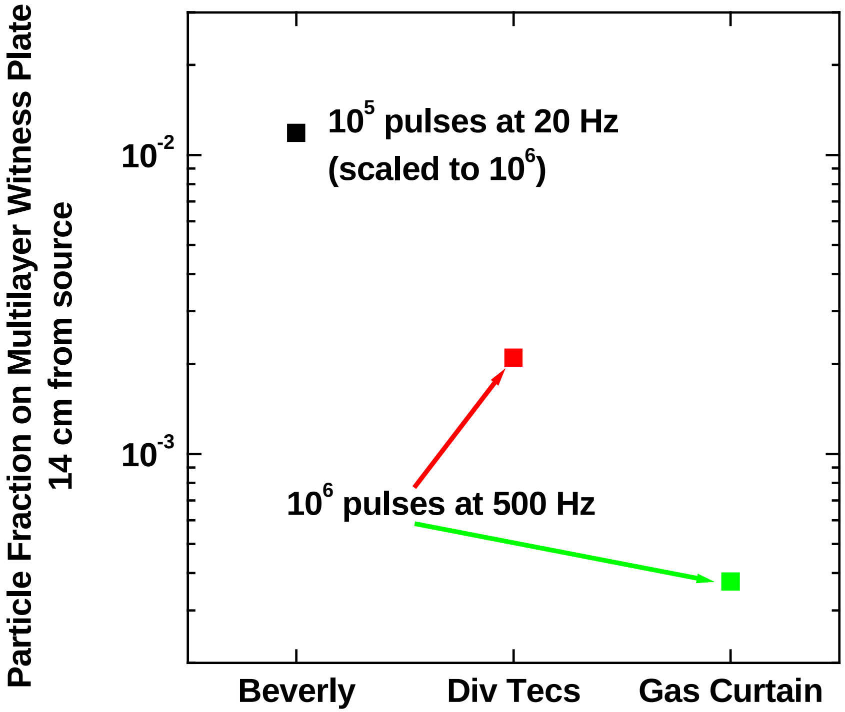
Flowing, EUV-transmissive gas used to sweep debris out of EUV beam path

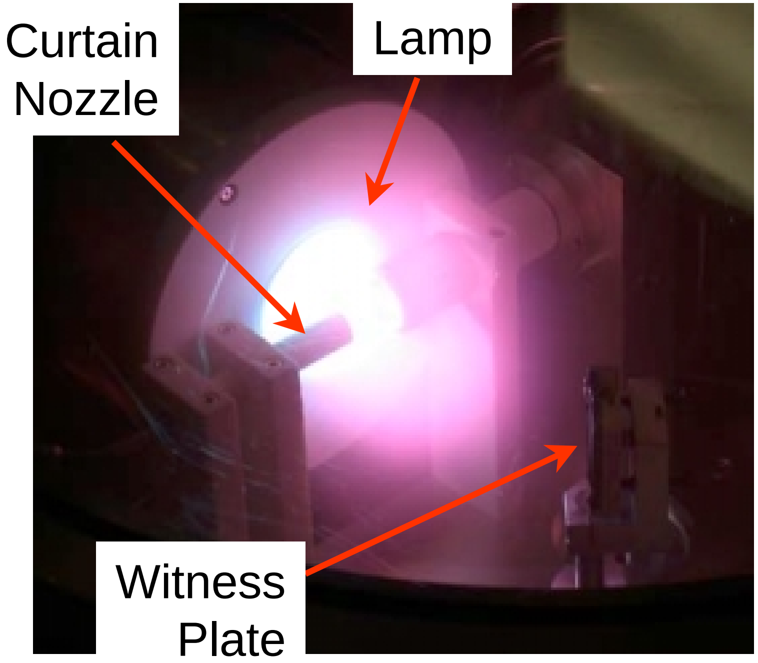




Plot of calculated "gas curtain" width for a fixed 60 degree deflection of 20 nm particle

New pulser and gas curtain combined to reduced particulate deposits by 32x …





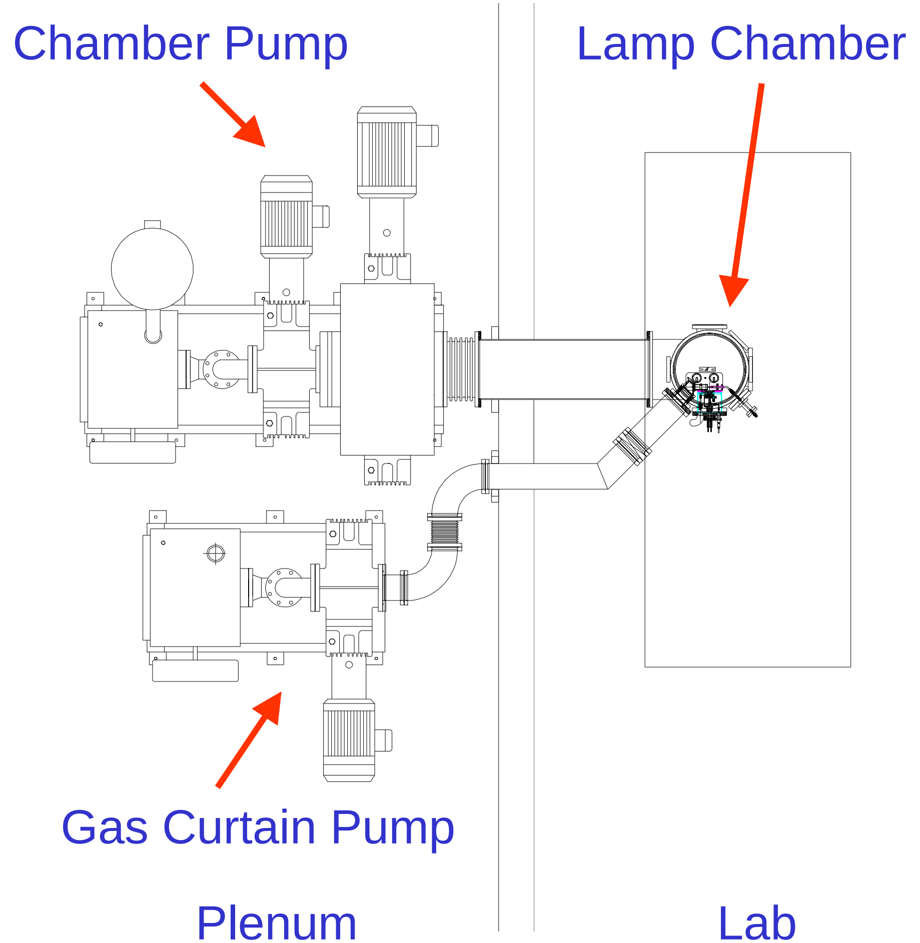
… and no detectible atomic debris with gas curtain operating

Source running at 500 Hz with gas curtain

Gas curtain mass flow capabilities increased by factor of >10x; Testing in progress

- Previous operating limit with He
  - 190 mTorr chamber pressure at 76 T-l/s
- Expected improvement
  - Chamber pressures at 760 T-l/s
    - Ar - 12 mTorr*
    - He - 31 mTorr*

    *90% trans. of EUV over 2m
- Further increase in flow possible with increased chamber pressure



Conclusions from first quarter of high power operation

- **Current rise time must be reduced and peak current increased to improve efficiency**
  - Max current at 2 μs pulse width only 4.5 kA
  - No significant EUV generation below ~3 kA
  - Want at least 5 kA in ≤1 μs wide pulse
- **Capillary erosion no longer most significant debris related issue**
  - No measurable increase in capillary diameter after 5×10^6 pulses with 1 μs pulse width at 500 Hz
  - Higher power deposition on electrodes responsible for increased debris generation
- **Electrode shape and material selection will be one of the most significant issues for all discharge sources**

Capillary Discharge development roadmap

Attribute/Year	Now	2002	2003	Commercial
Central Wavelength (nm)	13.5	13.5	13.5	13.5
EUV in-band power (W in π sr)	9(burst)	15	30	>50
Efficiency(J collected/J in)	.15%	.5%	1%	>1%
Available solid angle (ster)	π	π	π	π
Source emission area (mm^2)	0.5	0.4	0.3	0.2
Max. rep. Rate (kHz)	1.5 (burst)	1.5	3	5
Steady-state. rep. Rate (kHz)	1	1.5	3	5
Dissipated total power (W)	2000	3000	3000	5000
Radiated out-of-band power (W)	TBD	TBD	TBD	TBD
Surrounding gas and pressure	Xe, 10^{-4} mbar			
Condenser lifetime (pulses)	~10^6	10^8	10^{10}	10^{11}
Pulse-to-pulse intens.	6% 1σ	4% 1σ	2% 1σ	<2% 3σ
Pulse-to-pulse spatial	7% 3σ	4% 3σ	2% 3σ	2% 3σ
Pulse-to-pulse angular	TBD			
Pulse-to-pulse pointing	TBD			
Key risk areas				
Critical component life(pulses)	10^6	10^7	10^8	10^9

Summary

- Successfully generated 9 W of in-band EUV output over π sr
- 5 million pulse run completed with no erosion of capillary bore
- High-repetition-rate operation to 1500 Hz
- Debris deposition reduced by factor of 32 by using new pulser and gas curtain
- 6x increase in lamp efficiency and use of advanced capillary materials required for 50 W (2% BW, π sr) lamp output

International Sematech and the EUV, LLC are gratefully acknowledged for their support