Development of Efficient Fiber-laser-produced Plasma Source for EUV Radiation

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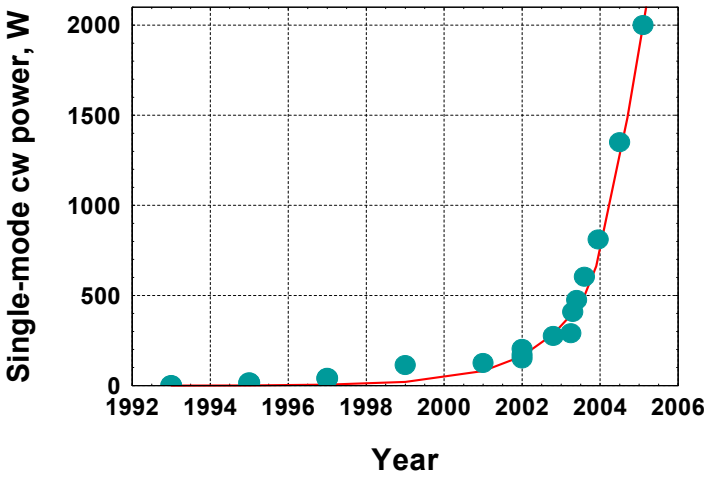
Objective of the Work

- Demonstrate feasibility of generating EUV radiation using fiber lasers

- Future applications:
  - High-power 13.5nm EUV sources for next generation lithography
  - Compact EUV metrology sources
  - Compact soft x-ray sources for nanoscale imaging

Fiber Laser Technology

- **Objective: High power FLPP**
- Practical technology:
  - Robust
  - Efficient (20% - 40% electrical-to-optical)
  - Compact
  - Lower cost
- Uniquely high powers:
  - Single-mode 1 - 2 kW achieved
  - >10 kW multi-mode (combined fibers) demonstrated



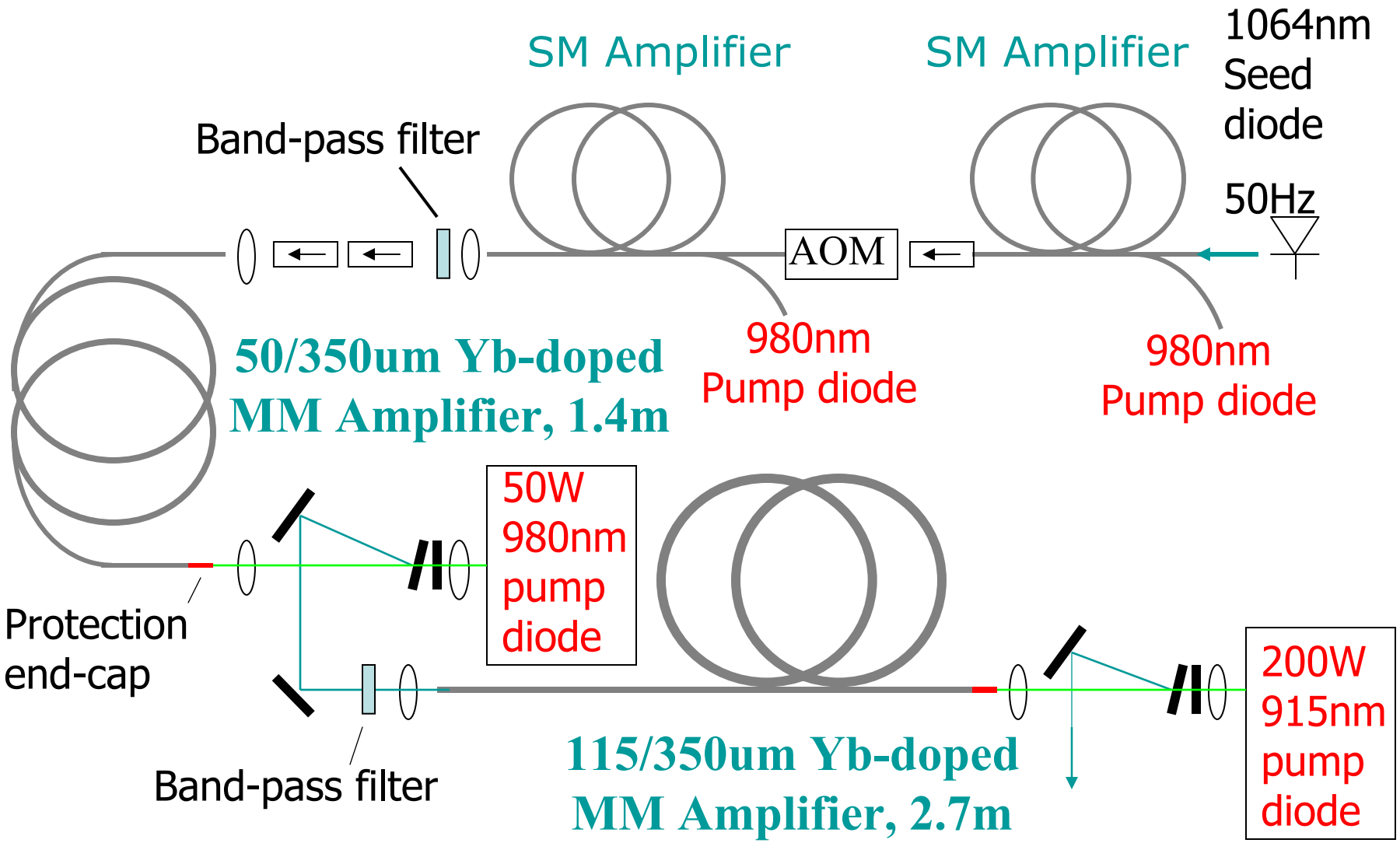
Pulsed Fiber laser

•ns pulses

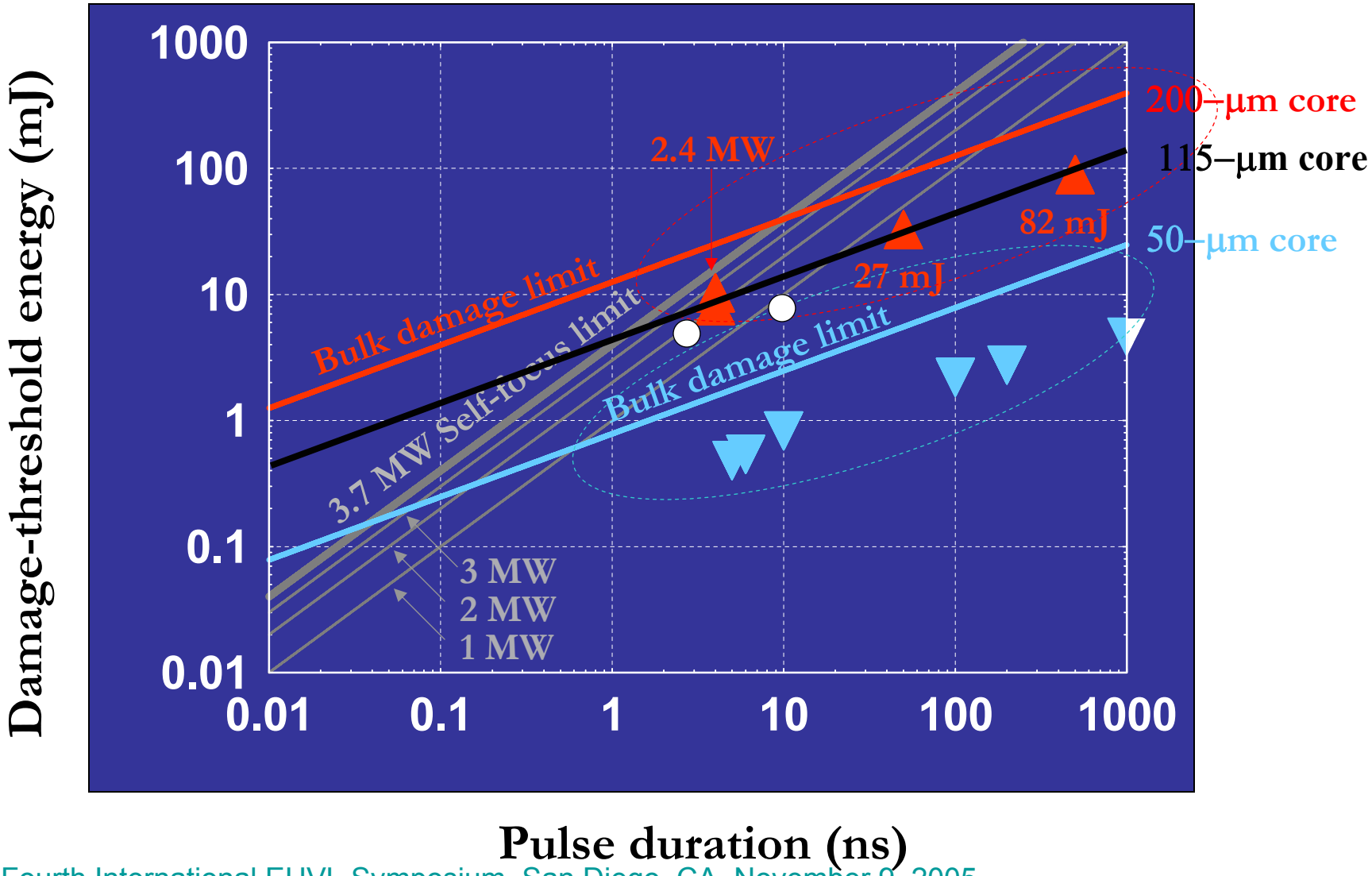
Required intensities on target: 10^{10} - 10^{12} W/cm^2

already demonstrated 1% CE EUV generation with FLPP

Nanosecond Fiber Laser EUV Driver



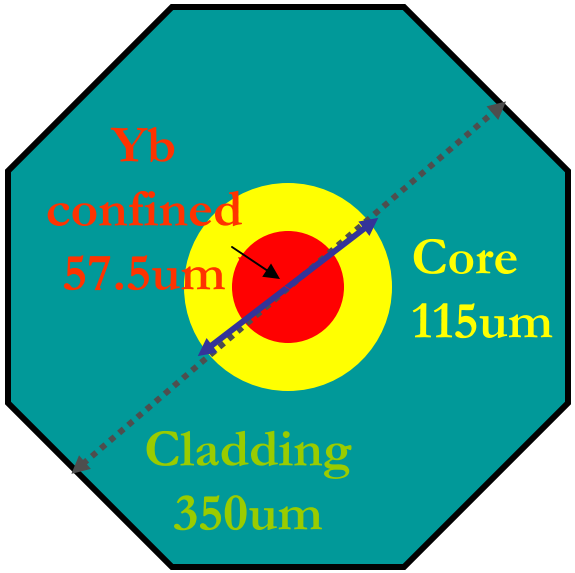
Achieved Pulse Energies and Peak Powers



Flexibility of Diode-Seeded Fiber System

- Arbitrarily controllable pulse duration
  - From 1ns to about 1 ms
- Controllable repetition rate
  - 1 Hz to about 1 MHz
- Arbitrarily adjustable pulse shape

High Energy ns-pulse Fiber

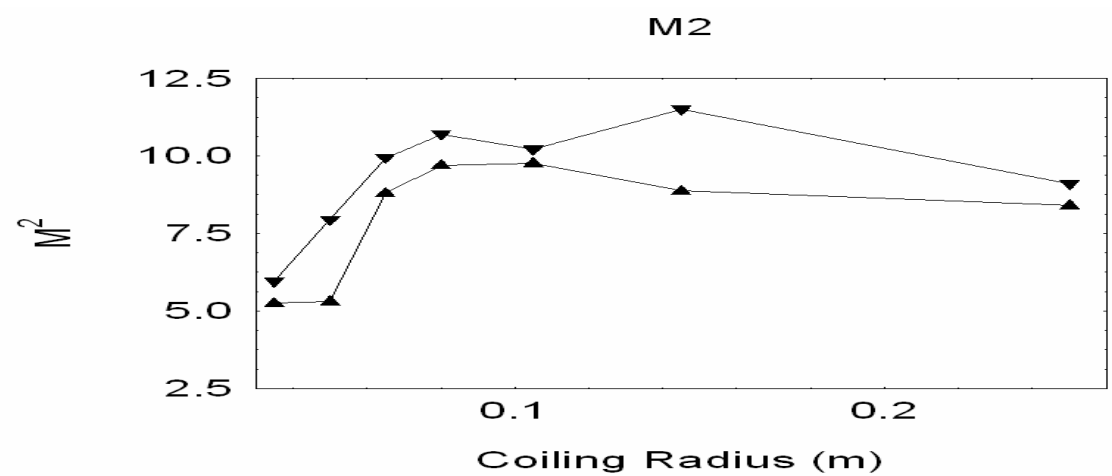


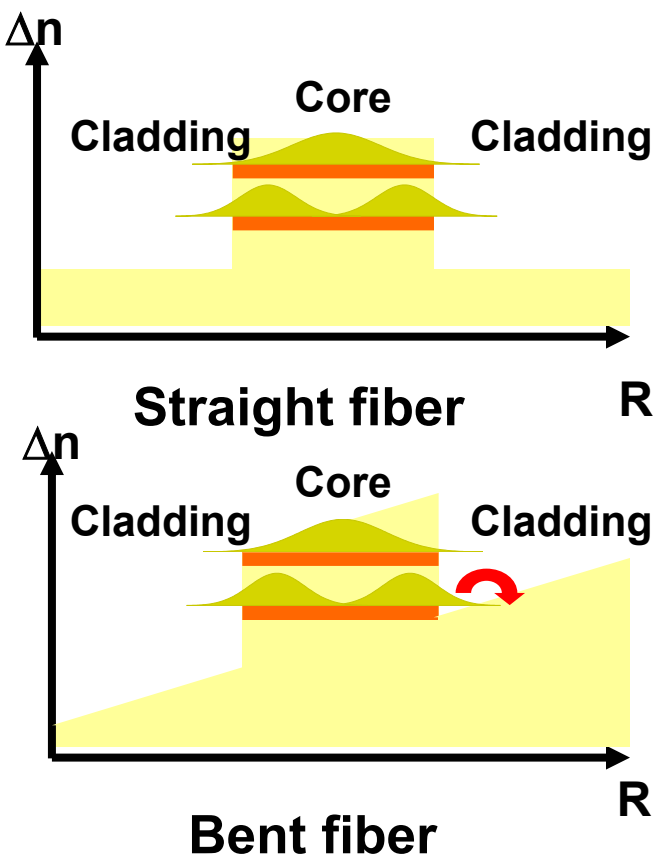
- **Step-index core diameter 115μm, NA 0.072**
- **Yb-doping confined to 57.5μm diameter**
- **Cladding diameter 350μm, NA 0.46**
- **Cladding Absorption @ 915nm: 5.7dB/m**
- **Supports >84 modes;**

  Coiling technique used to achieve good beam quality

Mode Control in Large Mode Area (LMA) Fibers

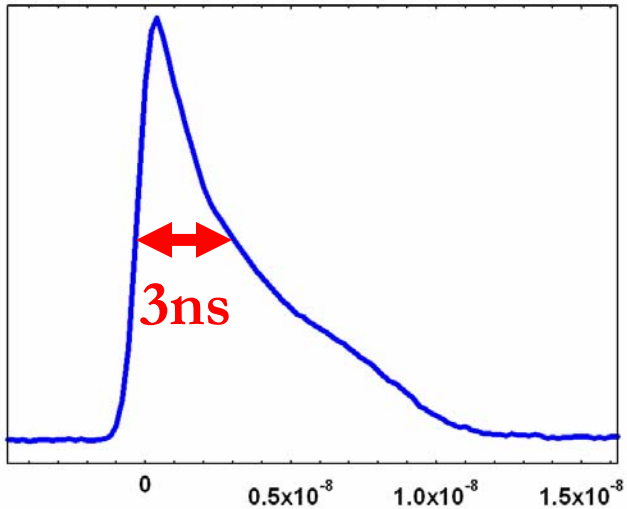
- **SM-output from LMA core:**
  - Mode-filtering in coiled low-NA LMA fibers
  - New fiber approaches (true SM LMA)





Fiber Laser Pulses for EUV Generation

- Pulse Energy 1-4 mJ
- Pulse Duration 3-6 ns (MW peak powers)



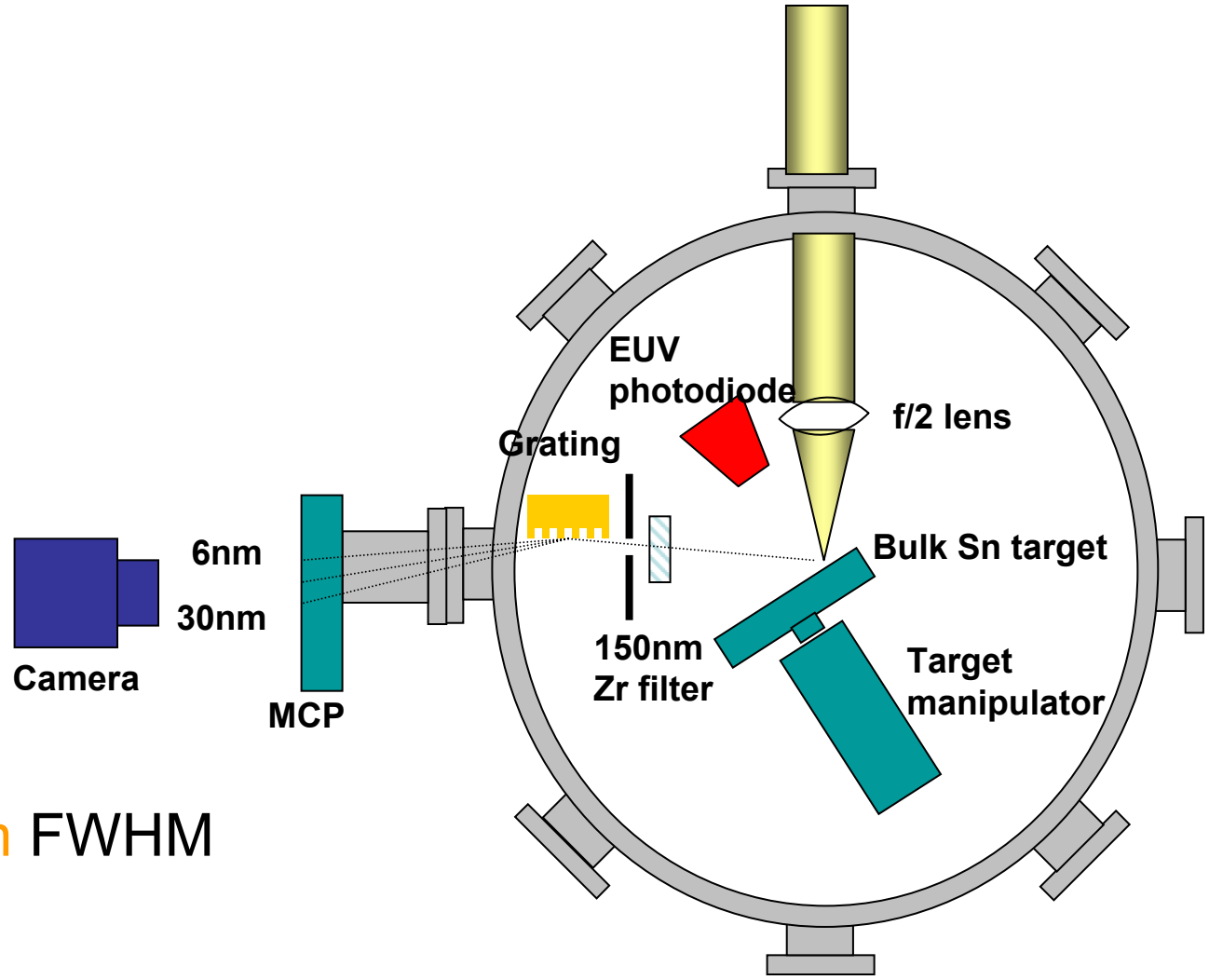
- Spot size on target: 35um FWHM corresponding to intensity of 1-2x10^{10} W/cm^2

EUV Target Chamber

Laser:
1064nm
50Hz
5mJ, 5 ns pulses

Target:

bulk Tin, Sn
45° incidence
f/3 focusing
Focal spot ~35μm FWHM



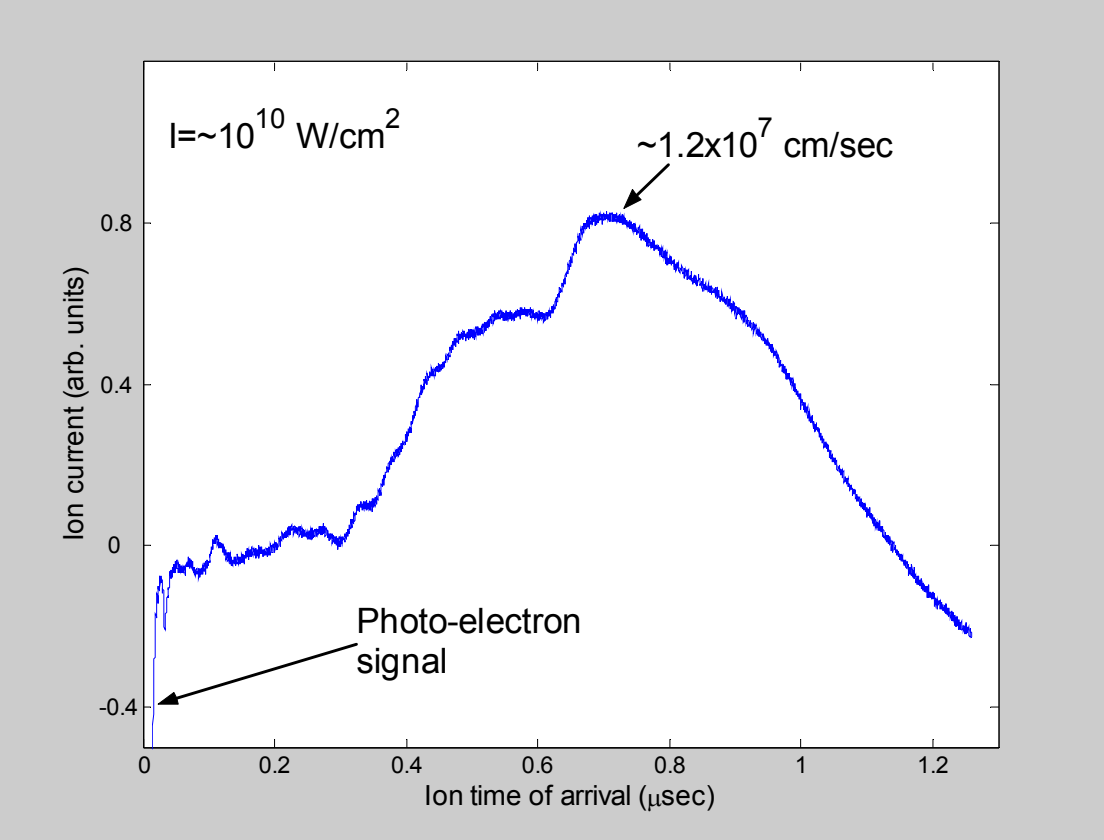
Ion Time-of-flight Measurement

2cm diam. Copper plate as a charge collector

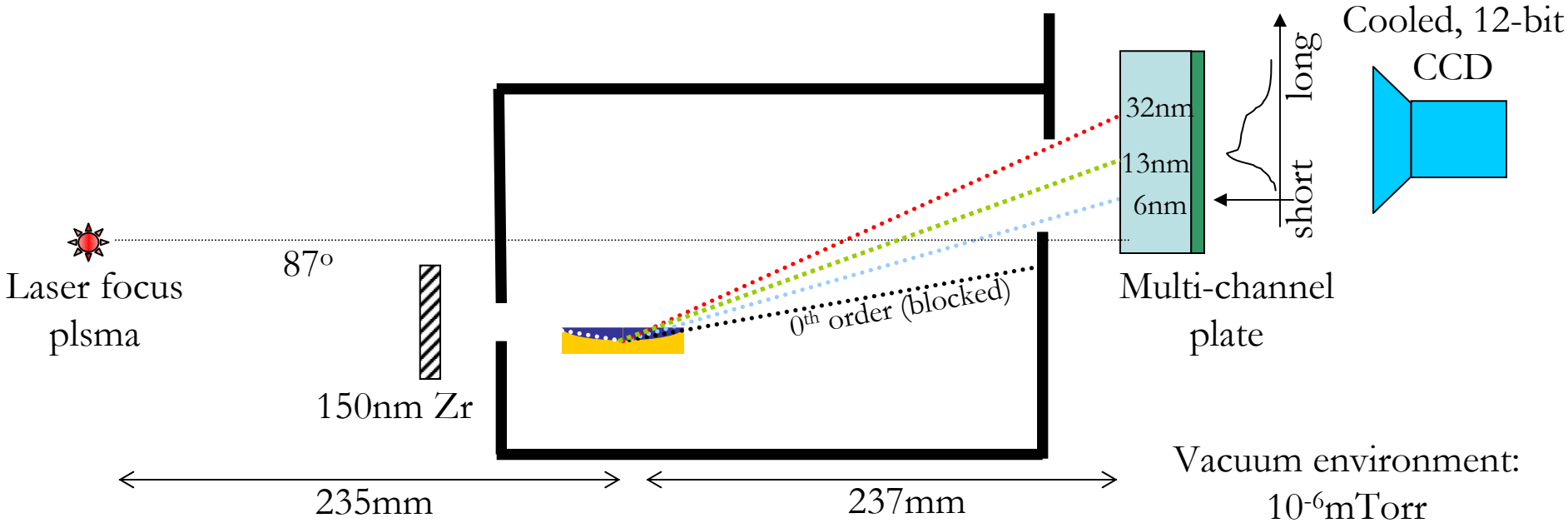
Detector at z=90mm

Normal to surface

Multi-keV ions:
(peak velocity:~10^7cm/sec)



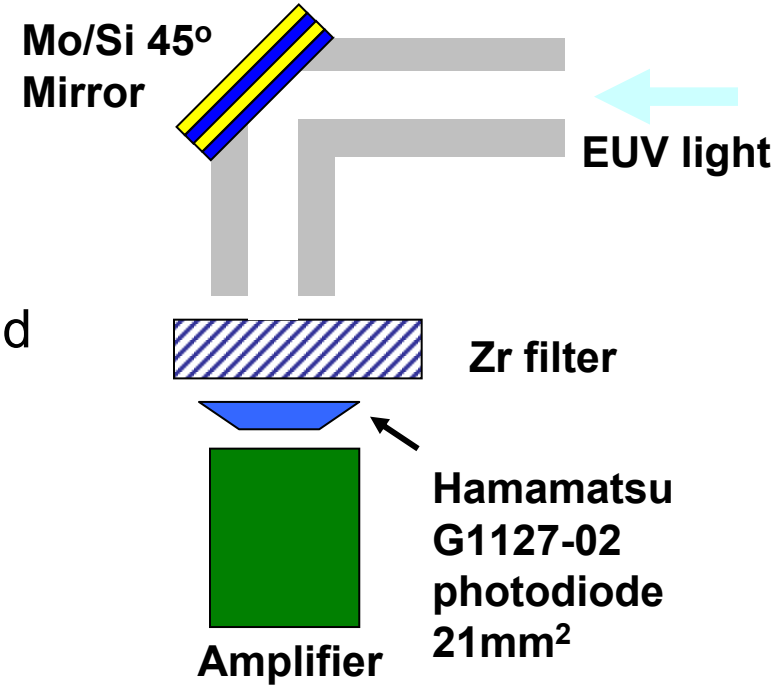
Spectrometer



Cylindrical flat-field, variable line-spacing grating (1200-l/mm)
Zr, Al filters for calibration and noise reduction.
Spectral range: 6-32nm

EUV Detector for absolute CE measurement

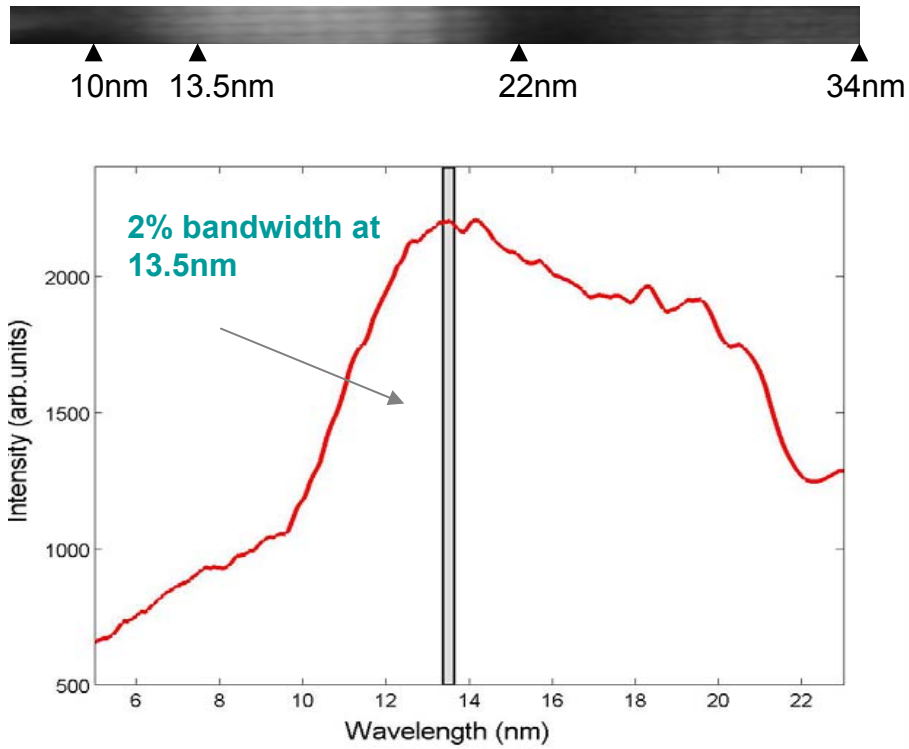
- Designed and built in house:
- Photodiode: GaAsP Schottky P.D. with quantum efficiency ~10.2 e^-/photon@13nm
- 150 nm Zr foil to block the ambient light
- Mo/Si multi-layer mirror only reflects in-band radiation.
- Trans-impedance electronic amplifier
- Sensitivity down to μJoule at 13nm
- Slow response: rise time ~300 nsec.



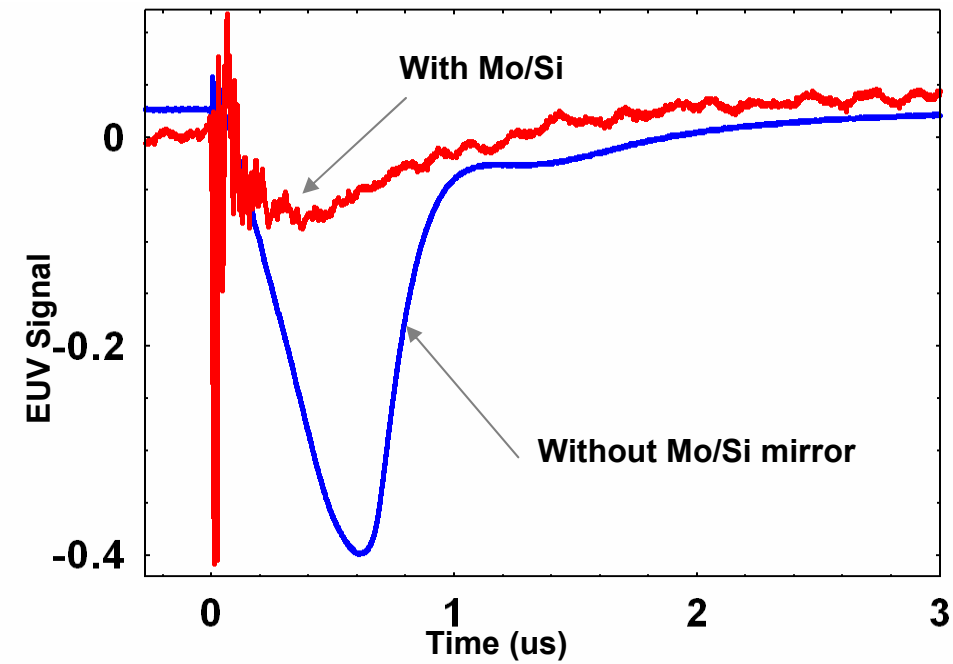
EUV detector

EUV Output

EUV Spectrum

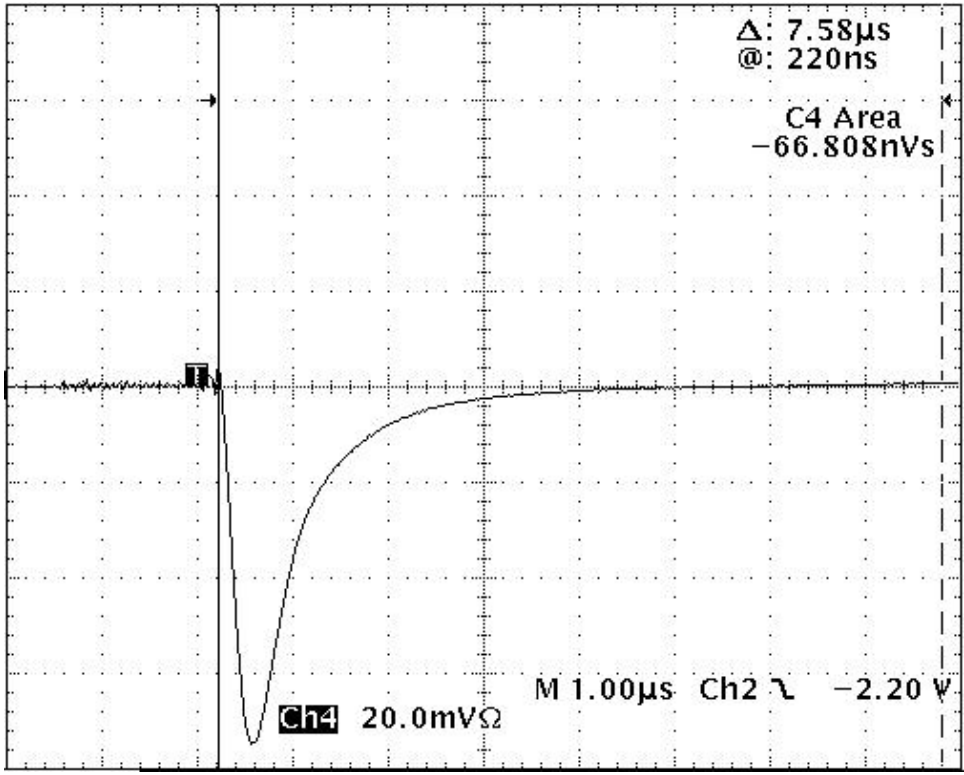


EUV Diode Signal



Conversion Efficiency

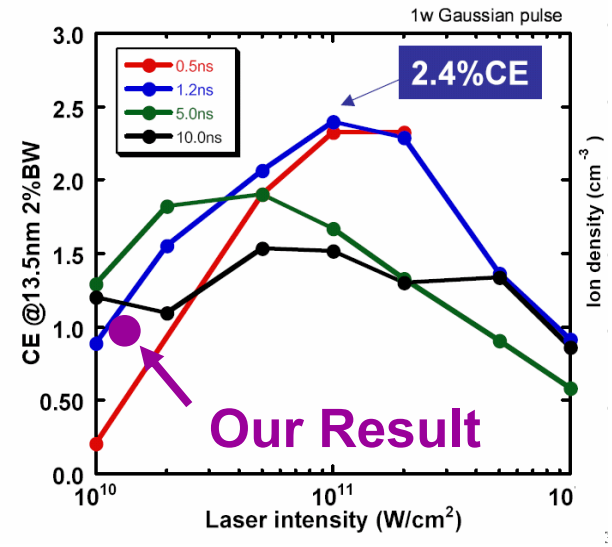
- Use a Xe pinch gas discharge source (courtesy of **Cymer Inc.**) to calibrate the EUV diode.
- Xe source output: 24mJ of EUV within 2% bandwidth in 2π sr.



Conversion Efficiency: ~ 0.9 % at 1×10^{10} W/cm^2

Yield Optimization: Higher intensities

- Experiment data agree with simulation result from Institute for Laser Technology, Japan*
- Increase intensity on target to increase conversion efficiency:
  - Increase pulse peak power up to ~2MW
  - Focus to smaller spot size by enhancing beam quality



***Atsushi Sunahara, Institute for Laser Technology Japan, at Sematech EUV Modelling Workshop Nov 2004**

Power scaling strategy

- **Multiple-fiber laser multiplexing:**
  - **Single-fiber emitters**
    - **300W – 400W average power and 3mJ – 4mJ per 5ns to 10ns pulse at 100kHz.**
    - **Requires special target design**
    -
  - **Wavelength multiplexing**
    - 5 to 10 single-fiber emitters spectrally combined into a single multi-wavelength beam.
    - 2 – 3 kW average power, 20mJ-30mJ pulse energy per spectrally-combined (SC) beam.
    - Requires combining elements withstanding kW-powers
  - **Spatial multiplexing on target**
    - 4 – 8 SC beams on target: 10kW – 20kW average power on target

Conclusions

- First demonstration of 13.5nm EUV generation an FLPP
- ~1% optical-to-EUV conversion efficiency (for 2% BW @ 13.5-nm) using a pulsed fiber laser
- Further CE increase is expected by optimizing pulse parameters
- High power fiber lasers – pathway to affordable high radiation power for EUV lithography

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