Extreme UV source based on fast capillary discharge plasma

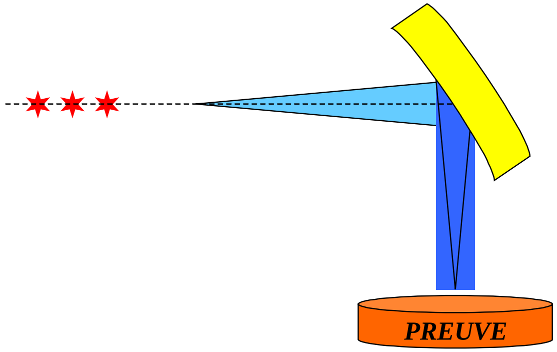
Smruti Ranjan Mohanty
Centre of Plasma Physics, Assam, India

- Research & developmental work carried out at GREMI, France during Dec.2000 to Nov.2001

Presentation Outline

- **Background**
- **Capillary Discharge Plasma System**
- **System Description & Diagnostics**
- **Investigations up to Nov. 2001 and Results**
- **Issues To Be Taken Up**
- **Summary**

Background



Importance of EUV source

Lithography

Material Processing

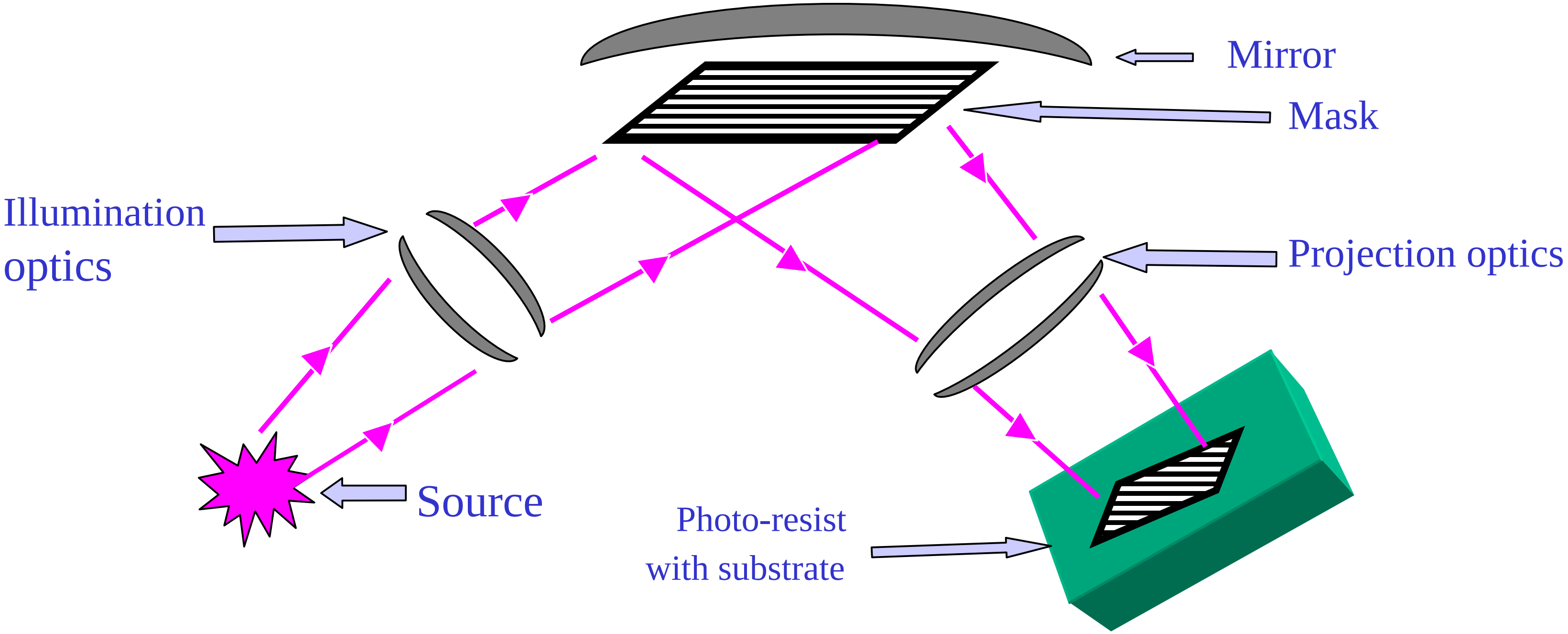
Lithography

? ? ?

Technique by which transistors are printed into chip

IC’s/Chips are indispensable in to-day’s life

How does optical lithography work ?



Mirror

Mask

Illumination optics

Projection optics

Source

Photo-resist with substrate

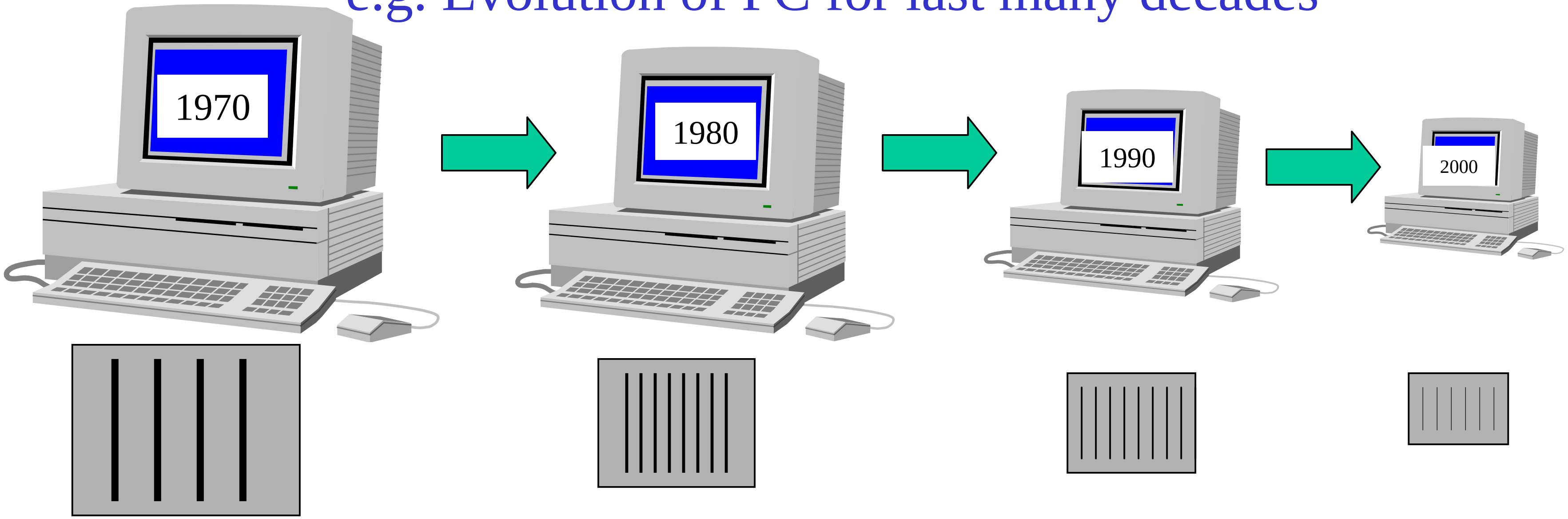
At present most advanced lithographic tool → 157 nm light to print features less than 100 nm.

What's the contribution of lithography to human life ?

- this technique makes our life faster and easier.

◁ ▷

e.g. Evolution of PC for last many decades



* 400 nm

* 300 nm

* 248 nm

* 157 nm

What would be the next the size of source ? **EUV light >>> Smaller features less than 70 nm**

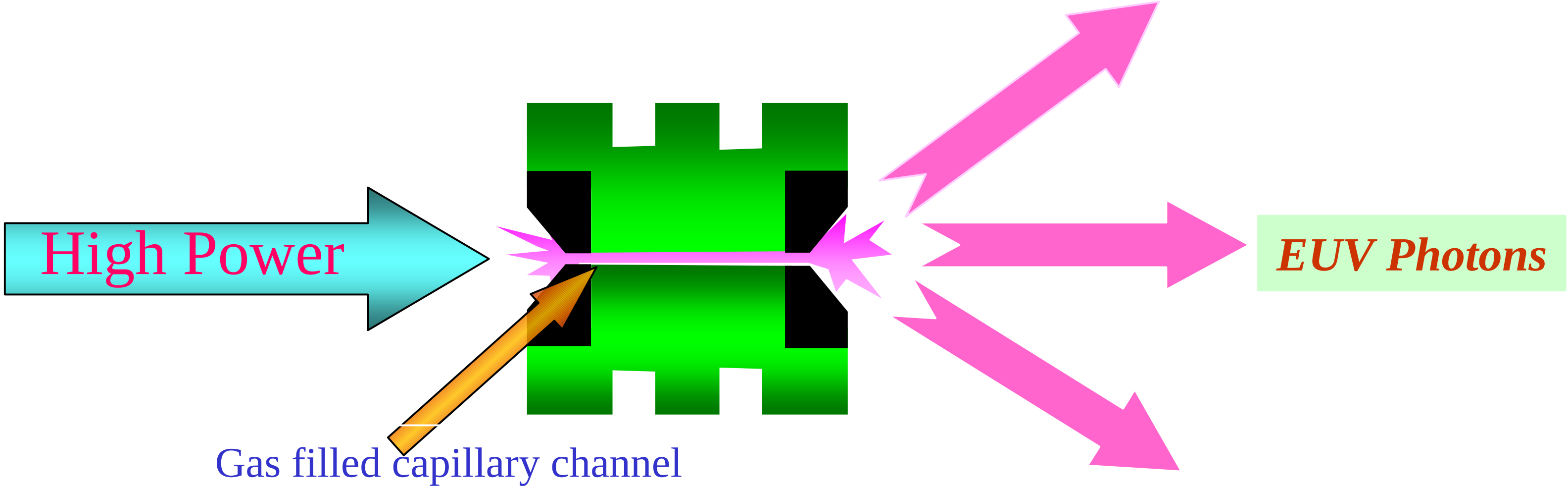
Relentless quest for light source of shorter wavelength to make our life more faster…….

What are the sources of EUV light ?

- ~~Synchrotron~~
- Laser Produced Plasma
- Gas Filled Electrical Discharge

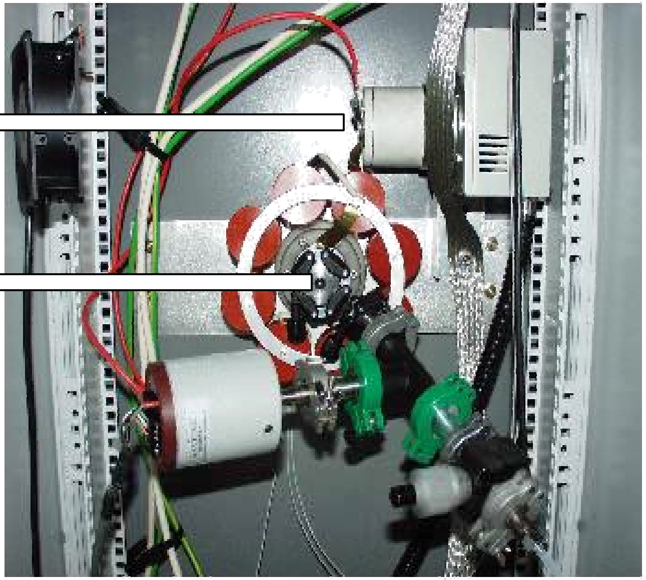
Gas filled electrical discharge, in particular Capillary discharge → Simpler in design, cost-effective & compact

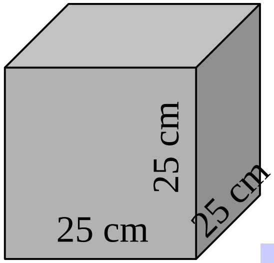
Principle of capillary discharge device

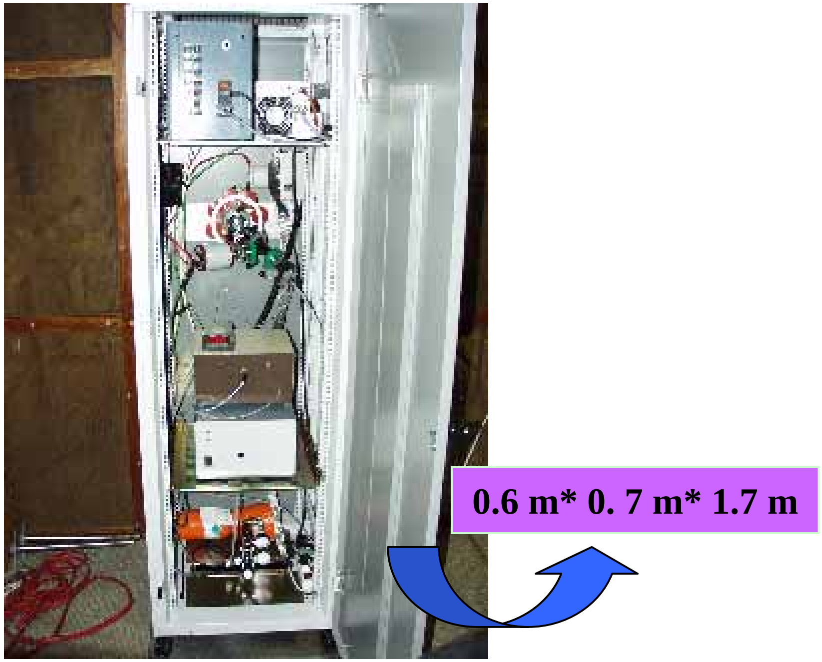


- High power density of several GW/cc are injected to capillary channel that leads to create plasma of higher degree of ionization and thus emits radiation mostly in EUV.

GREMI EUV Source looks like……..



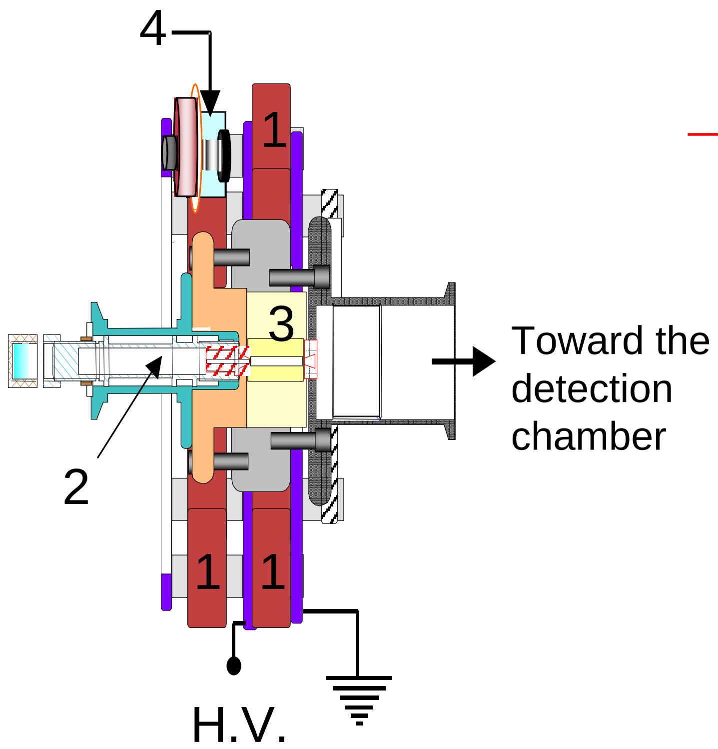




- *Much compact*
- *Simpler in design*
- *Cost-effective*
- *Easy to operate*

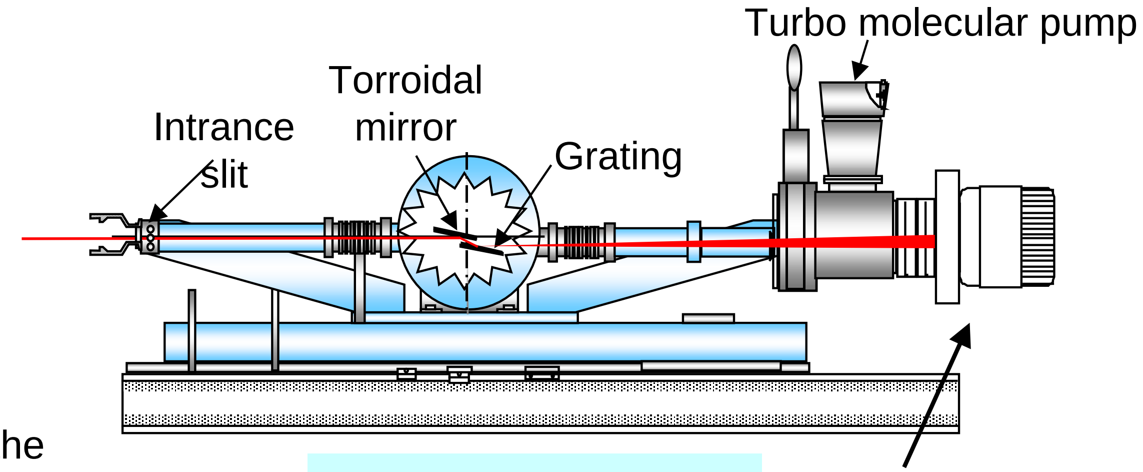
Schematic of Capillary system alongwith some diagnostics

Capillary With Capacitor bank

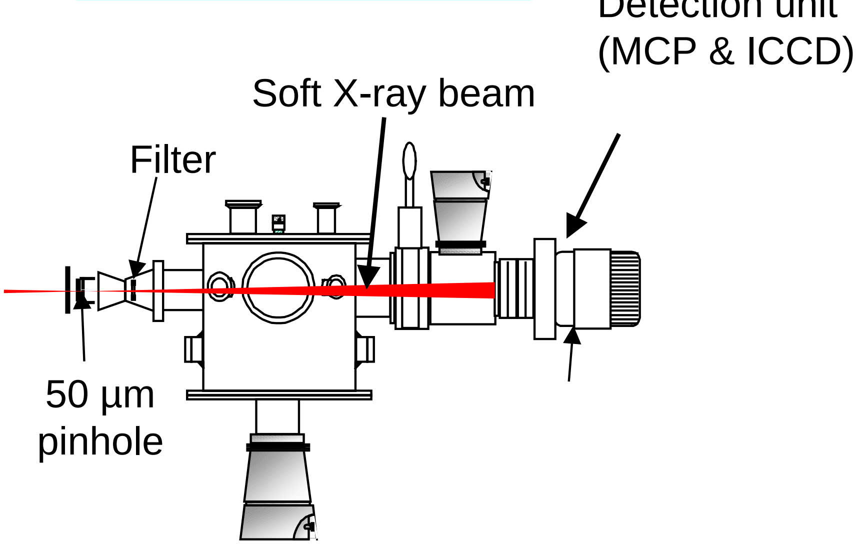


1. Knob capacitors
2. Xenon
3. Capillary
4. Fast switch

EUV Spectrometer



Pinhole imaging facility

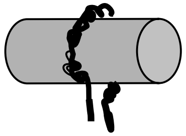


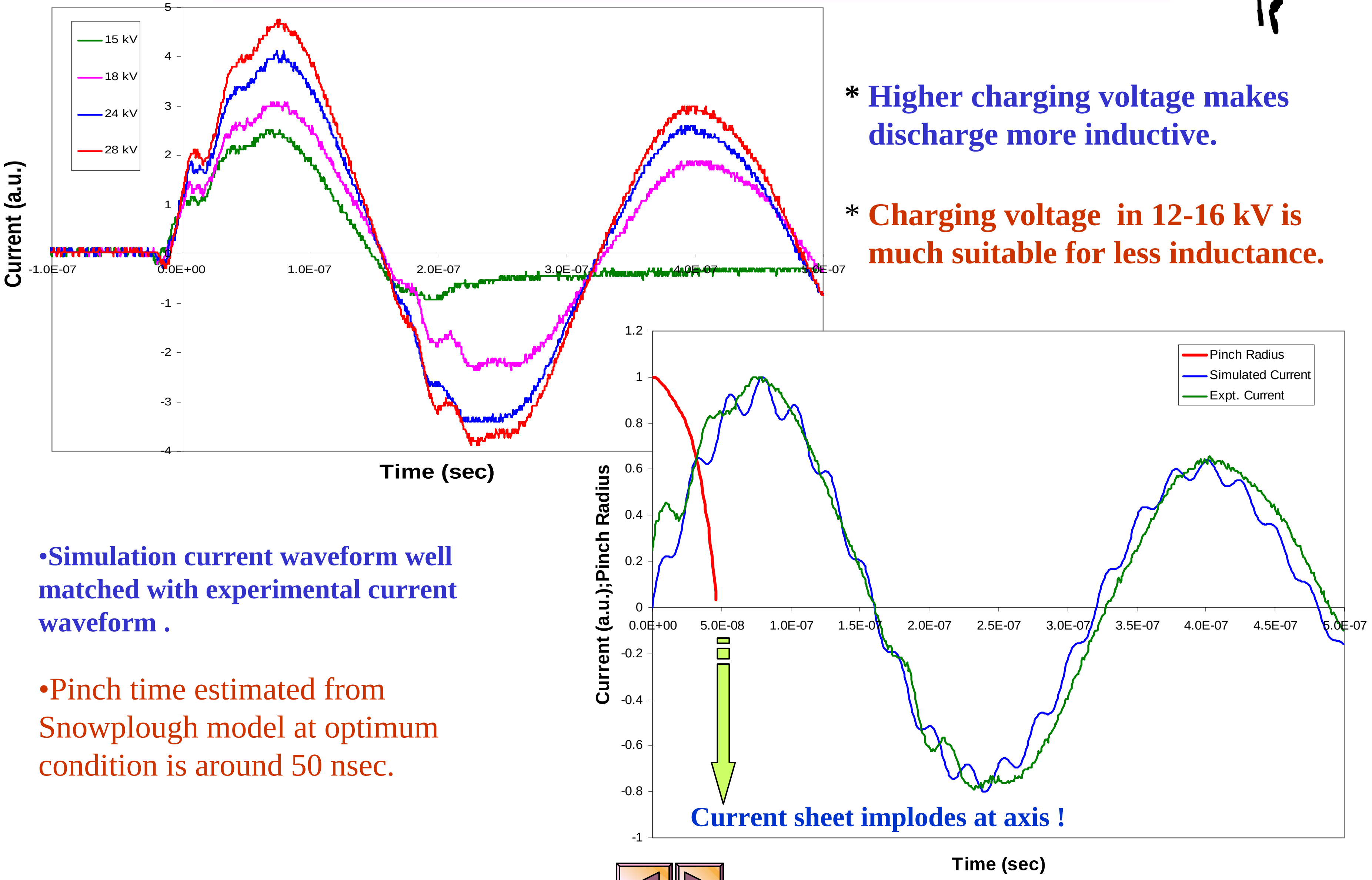
Investigations to date

- Capillary of different materials and dimensions
- Electrical & Energy measurements
- TI &TR EUV spectroscopic measurements
- Time & Space resolved pinhole measurements
- High repetition rate operation
- Debris collections

Results

Discharge current across the capillary was monitored by a Rogowski coil





Current sheet implodes at axis !

* **Higher charging voltage makes discharge more inductive.**

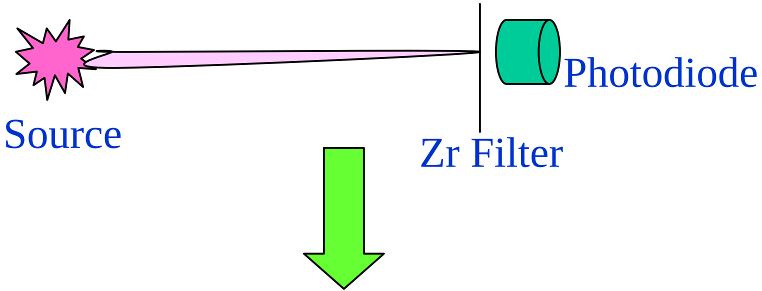
* **Charging voltage in 12-16 kV is much suitable for less inductance.**

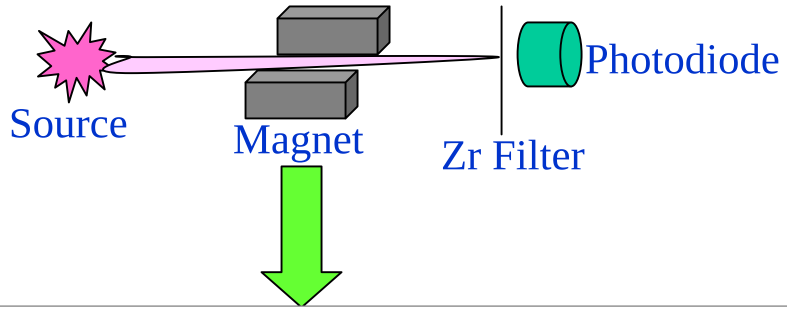
- **Simulation current waveform well matched with experimental current waveform .**

- Pinch time estimated from Snowplough model at optimum condition is around 50 nsec.

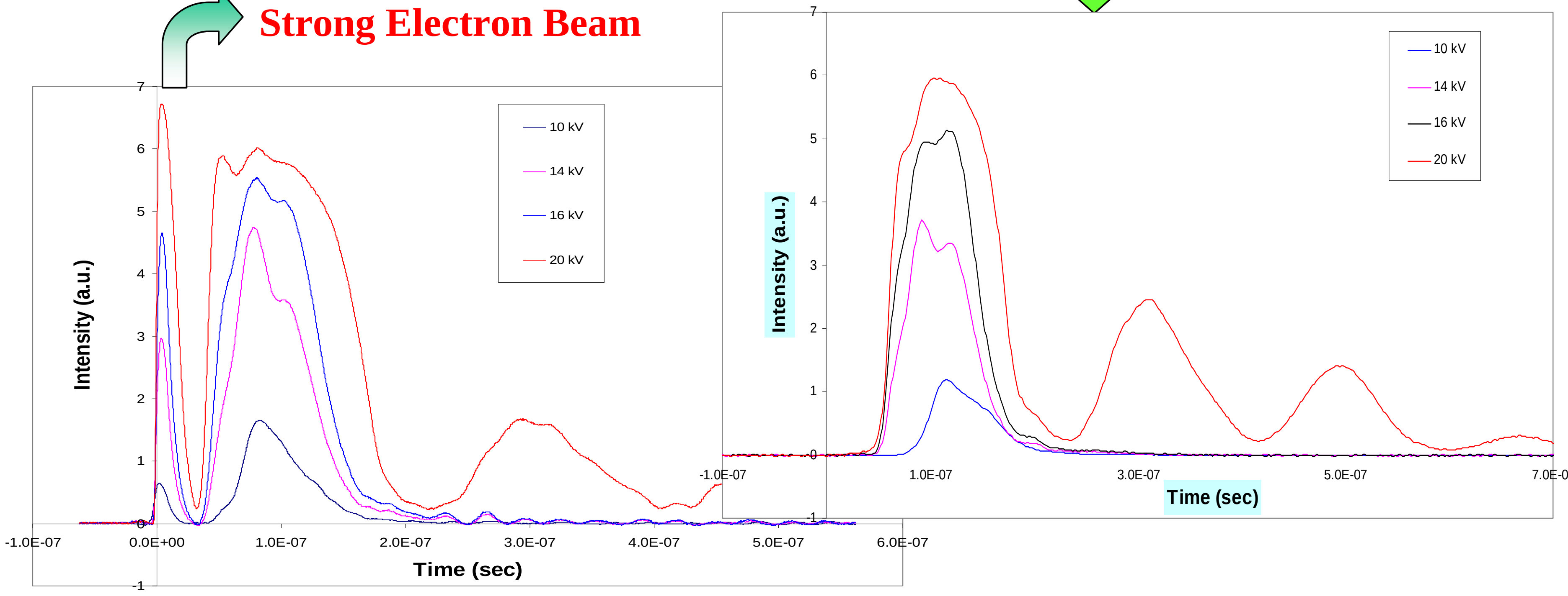
Results

Observation of streamer of electrons...



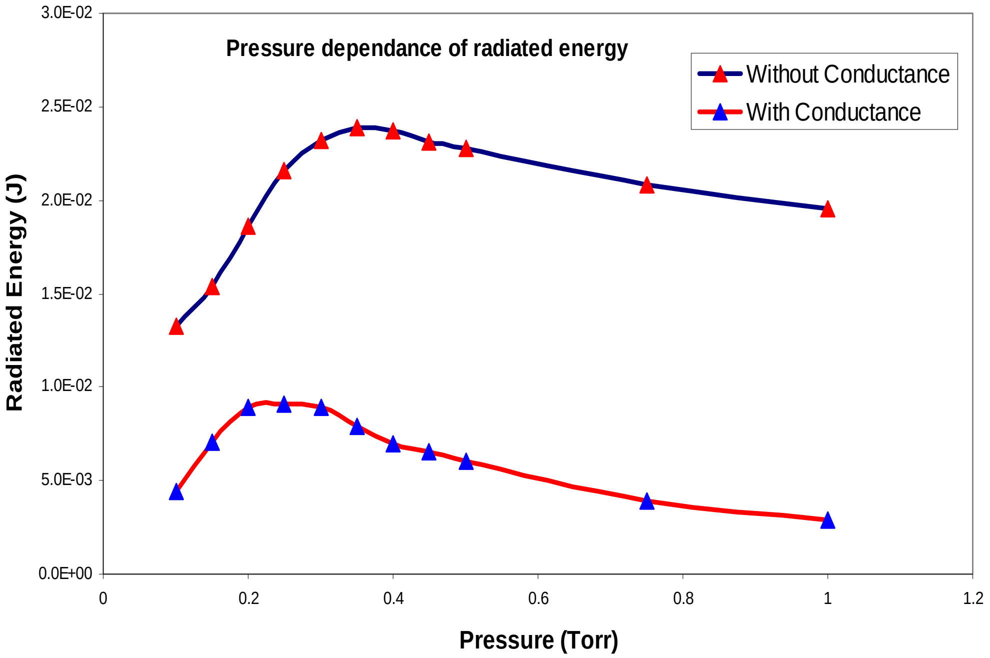


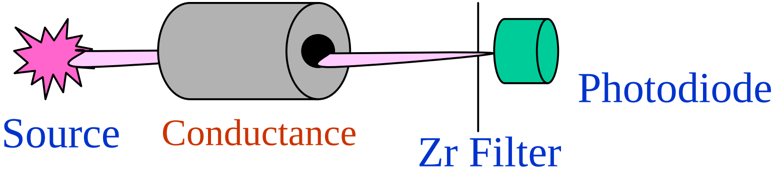
Strong Electron Beam



Results

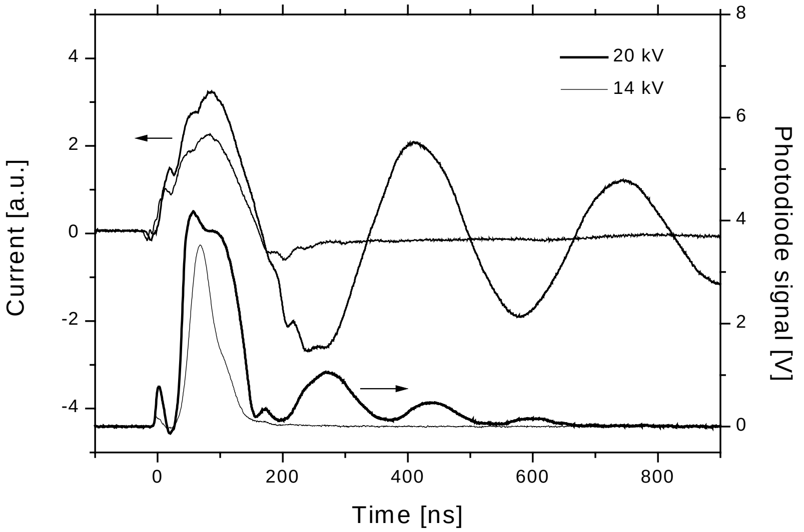
Pressure dependence of EUV radiation




Source
Conductance
Zr Filter
Photodiode

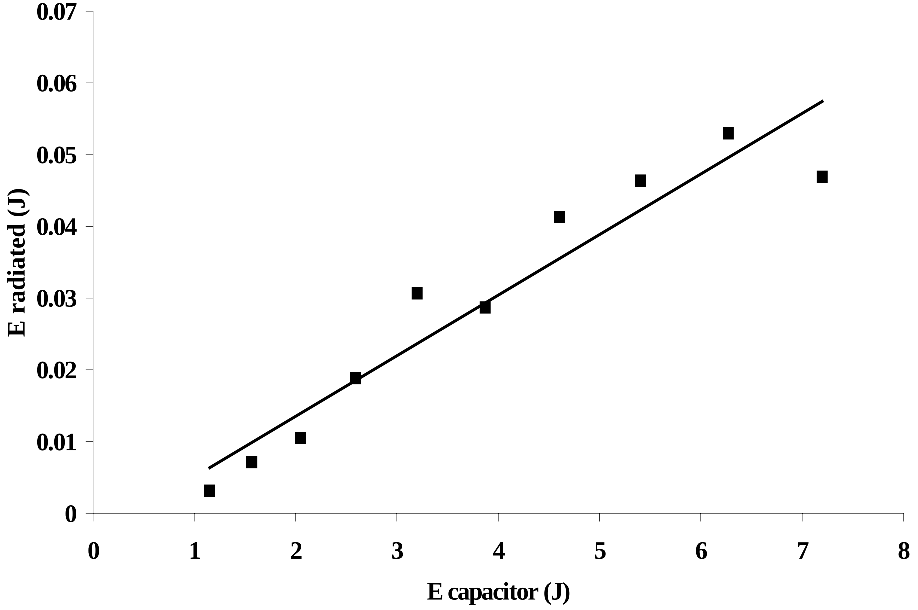
Radiated Energy increased by a factor of 2 only in absence of conductance.

Current waveform and photodiode signal for different charging voltage

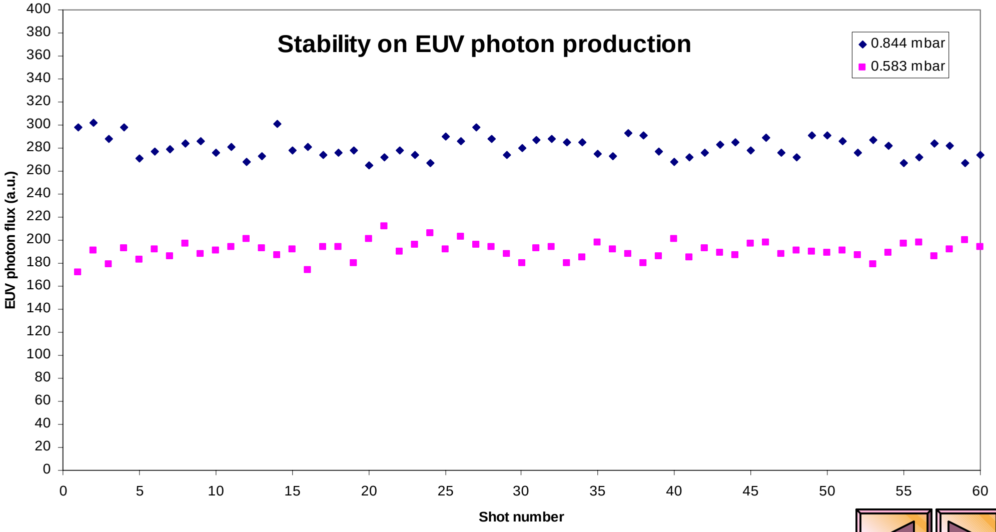


Results

Linear dependence of $E_{radiated}$ with E_{input}



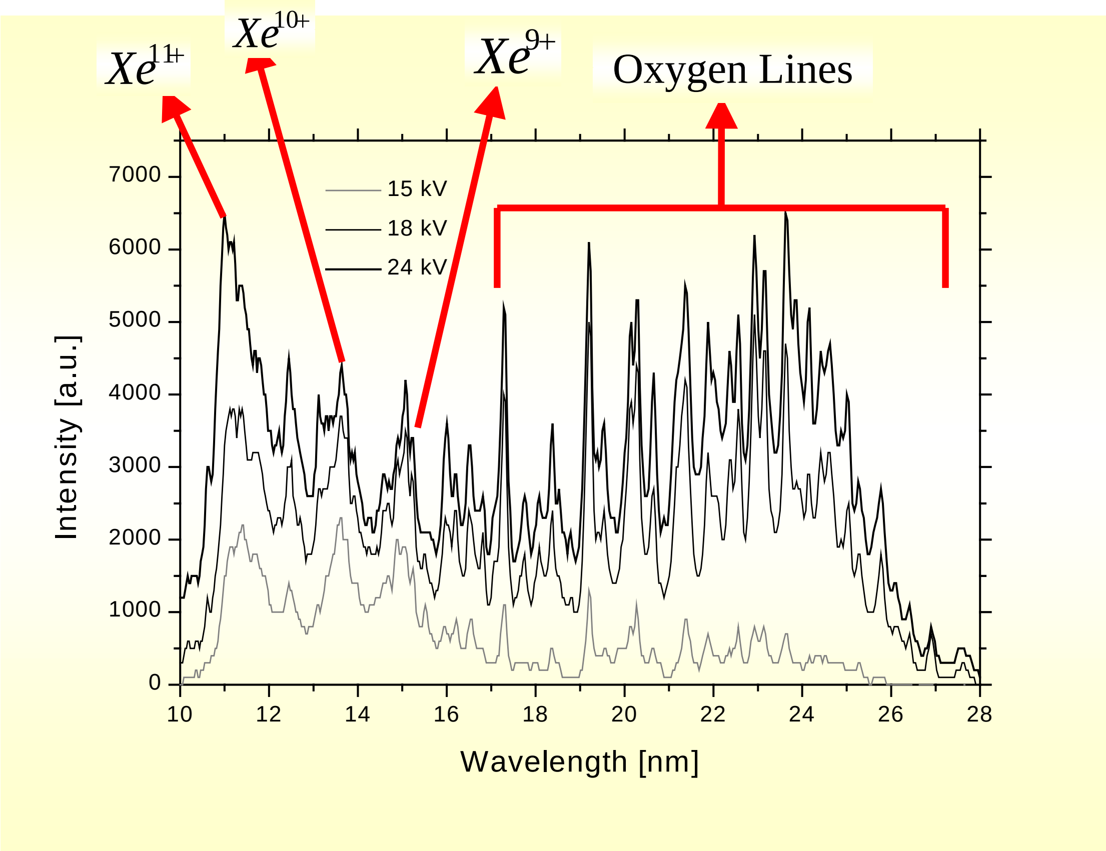
Conversion efficiency from $E_{input} \Rightarrow E_{Photon}$ is around 2.0%.



Shot to shot fluctuation in photon flux is around 4%.

Results

Time integrated xenon spectra at 0.46 mbar for different charging voltages



- Three broad band peaks of Xe centered at 11, 13.5 &15 nm

- Oxygen lines from wall

- Xe/O lines intensity increases with the increase in voltage

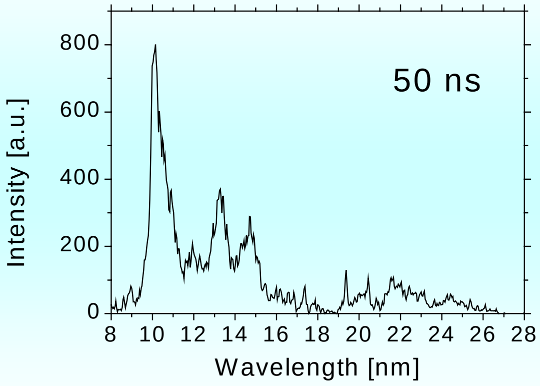
- Observation of 11 nm peak indicates that plasma temp. of 45 eV

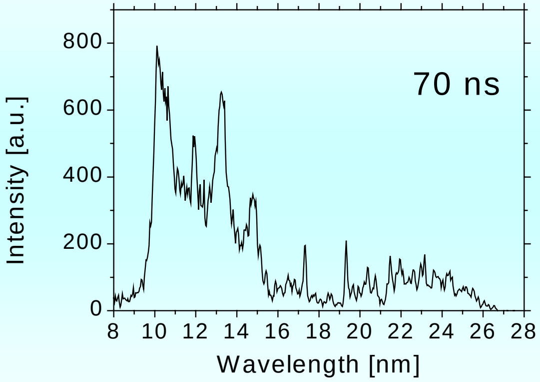
- In-band radiated energy at 13.5±0.45 nm >>>> 0.5 mJ/sr to 20 mJ/sr per pulse

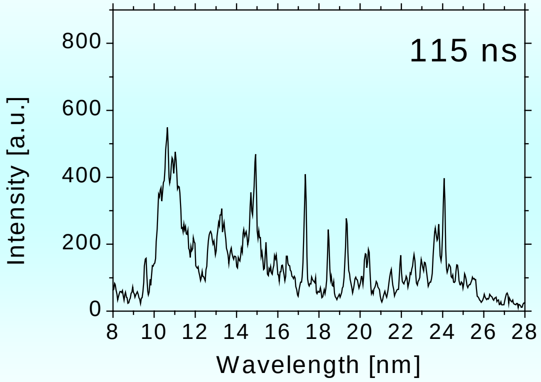
{Robert et al., SPIE 4343 (2001) 566-575}.

Results

Time resolved spectra at 0.46 mbar and 24 kV charging voltages







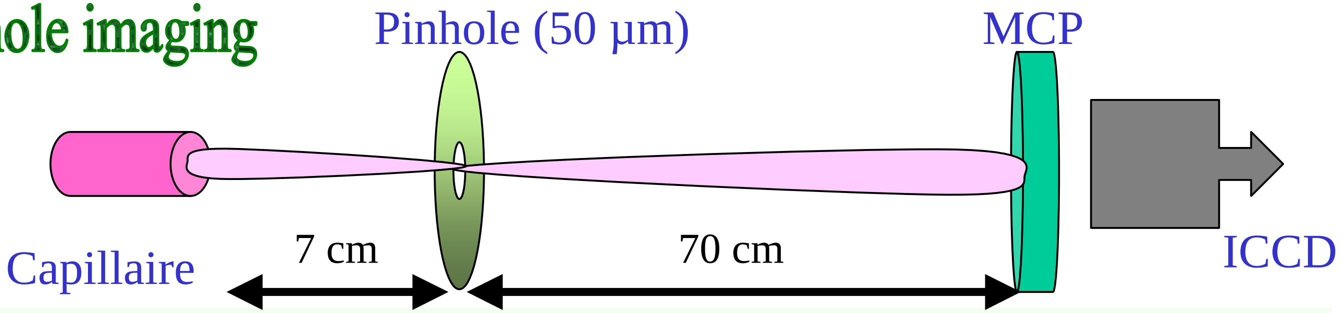
- 11nm broad band peak appears first & it goes maximum at the maximum of compression.
- At the instant of maximum of discharge current the 13.5 nm peak appears to be prominent.
- Spectra trapped after first half cycle of current do not show any emission from broad bands.

{Mohanty et al., Microelectron. Eng., 65 (2003) 47-59}

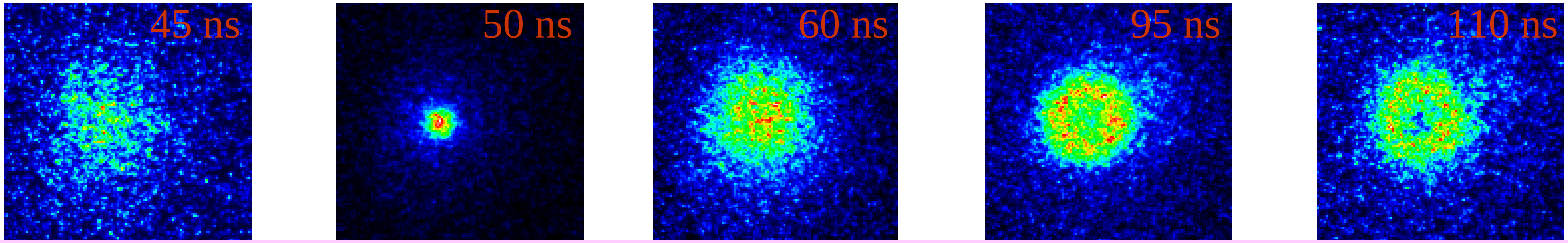
Results

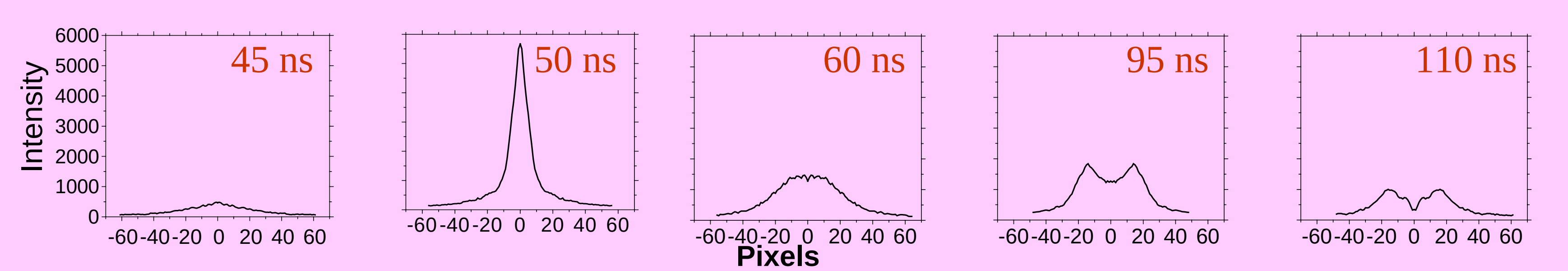
Pinhole imaging

Pinhole imaging



Time resolved pinhole images from 10 mm long 1.2 mm diameter alumina capillary at 1 torr Xenon and at 24 kV charging voltage...





- A second faint compression observed at the maximum of discharge current.
- The beam intensity profile changed from single peak pattern to annular pattern.

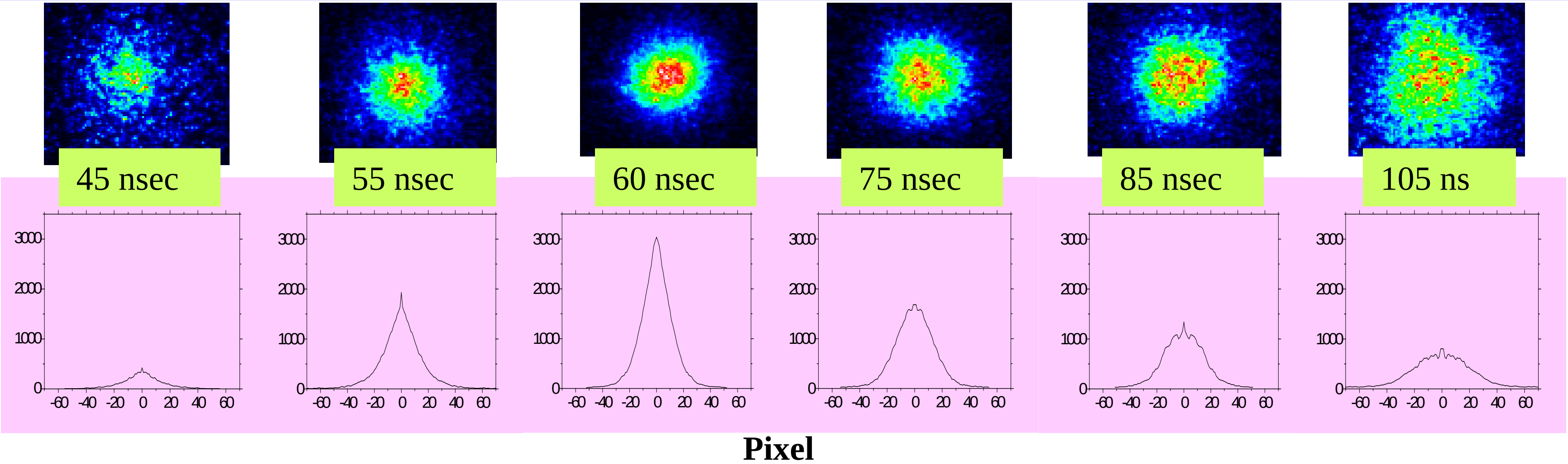
Annular pattern may be due to increased refraction of EUV beam caused by larger density in plasma column.

Results

Pinhole imaging

Pinhole imaging

Time resolved pinhole images from 10 mm long 1.2 mm diameter alumina capillary at 0.3 torr Xenon and at 24 kV charging voltage...

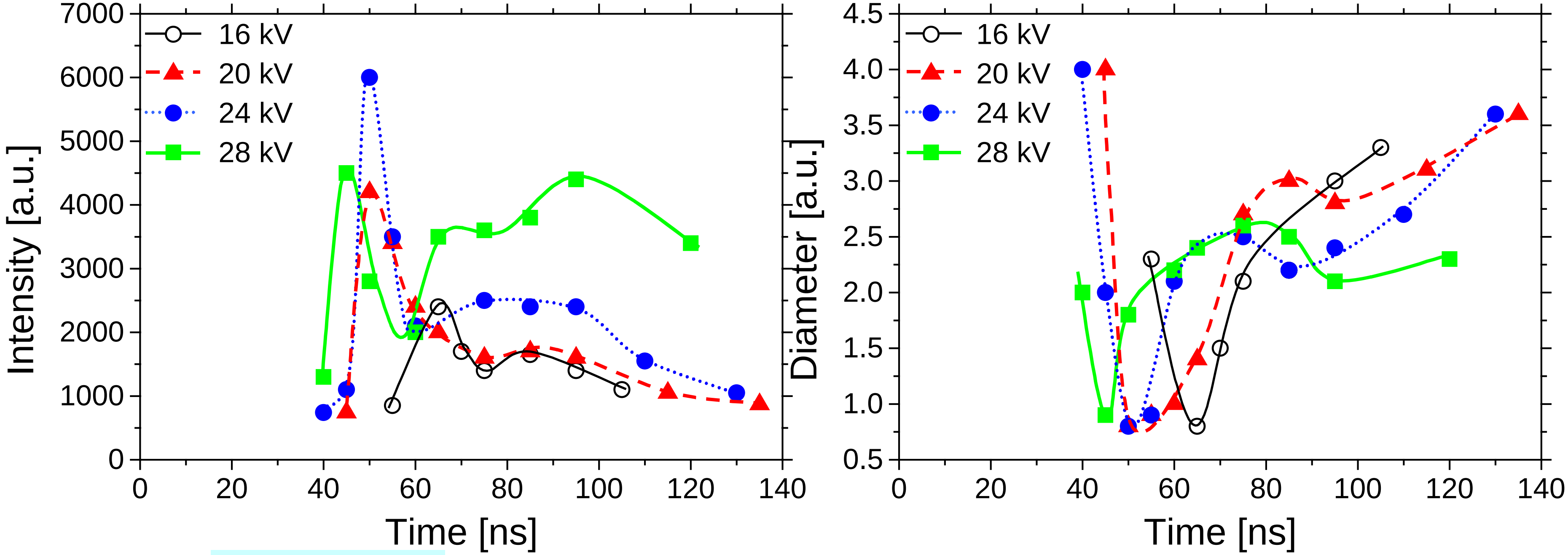


At lower filling pressure evolution of plasma inside capillary is much similar to higher pressure in exception with minor second compression and annular beam profile structure.

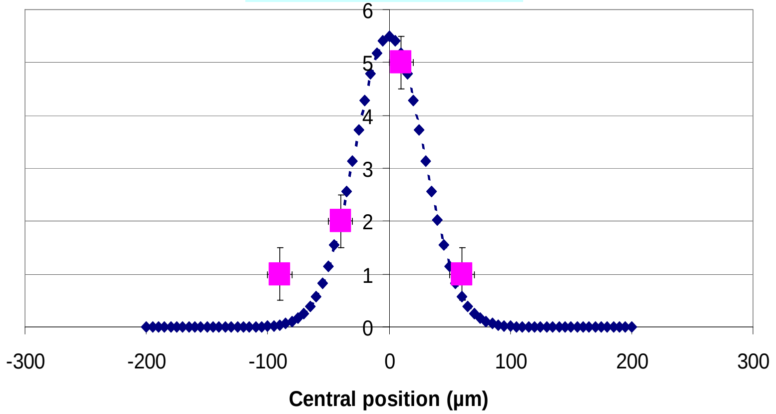
- Rapid Contraction → Heating of Plasma → Slow expansion
- Super fast pinching effect is observed only at higher pressures.
- Plasma reaches at axis around 50-60 ns of start of discharge current.
- Second minor compression is marked only at higher pressures (>1mb).

Results

Effect of charging voltage on intensity and pinch diameter…..



Stability of Source

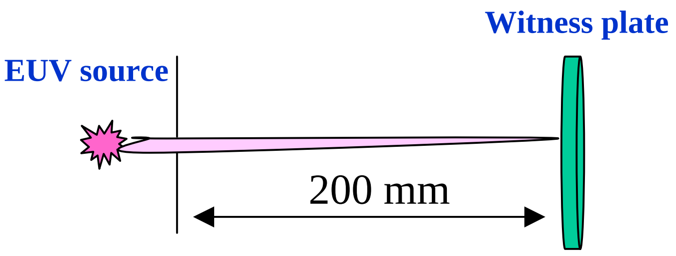


<< Deviation of mean position from ~45 μm

Results

Key factors for commercial implementation of any EUV source are…

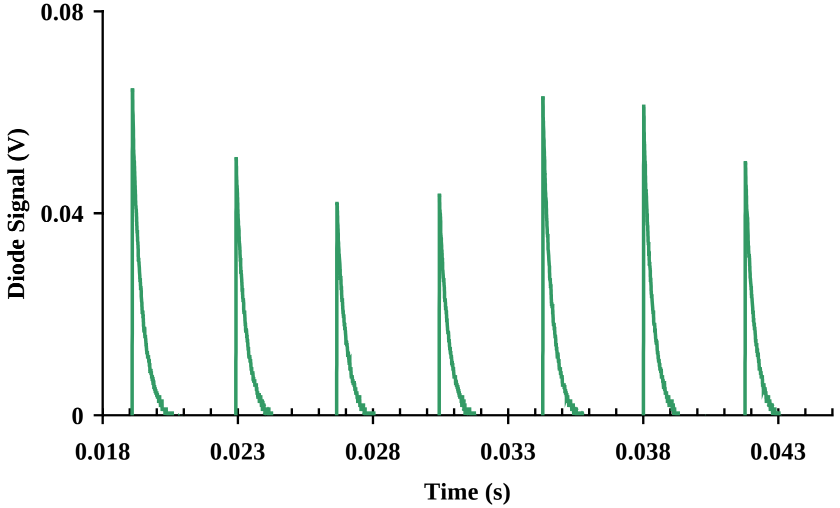
- **debris minimization**
- **operation in high repetition rate**



In 10 Hz for 3 hours/10000 shots...

11 nm thick debris (0.011 □/pulse)

Photodiode signal of repetitive operation at a frequency of 266 Hz



Till date we have achieved 350Hz in burst mode and 50 Hz in continuous mode of operation.

Higher repetition rate operation is in progress with cooling electrode.

Issues to be taken up

- Scaling up EUV power output at 13.5 nm
- Debris minimization
- Operation in high repetition rate

Summary

- Compact, cost-effective, simple and low inductance EUV lamp has developed.
- Electrical and spectroscopic studies show encouraging results.
- Pinhole measurements reveal strong contraction of plasma.
- Positional and Emission stability of source is excellent.

◁