Accelerator-based lithography and the Induction Storage Ring Light Source

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U.S. DEPARTMENT of ENERGY

Outline

- Semiconductor lithography and the existing source for EUV light, laser produced plasma (LPP)
- Generating light for lithography from particle accelerators
- Challenges adapting accelerator-based light sources to semiconductor factories
- Survey of private and public sector efforts
  - Induction Storage Rings and SSMB EUV

NOTE: Image credits compiled in last slide.

EUV Lithography and Laser Produced Plasma Source

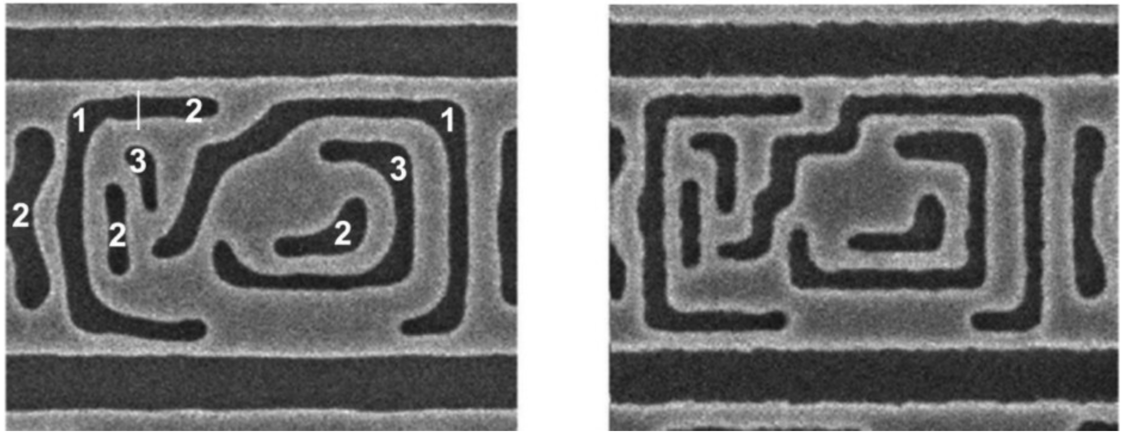
- Lithography scanners use photons to etch patterns onto silicon wafers during semiconductor manufacturing

Size R of smallest features

$$R = k_1 \frac{\lambda}{\mathrm{NA}}$$

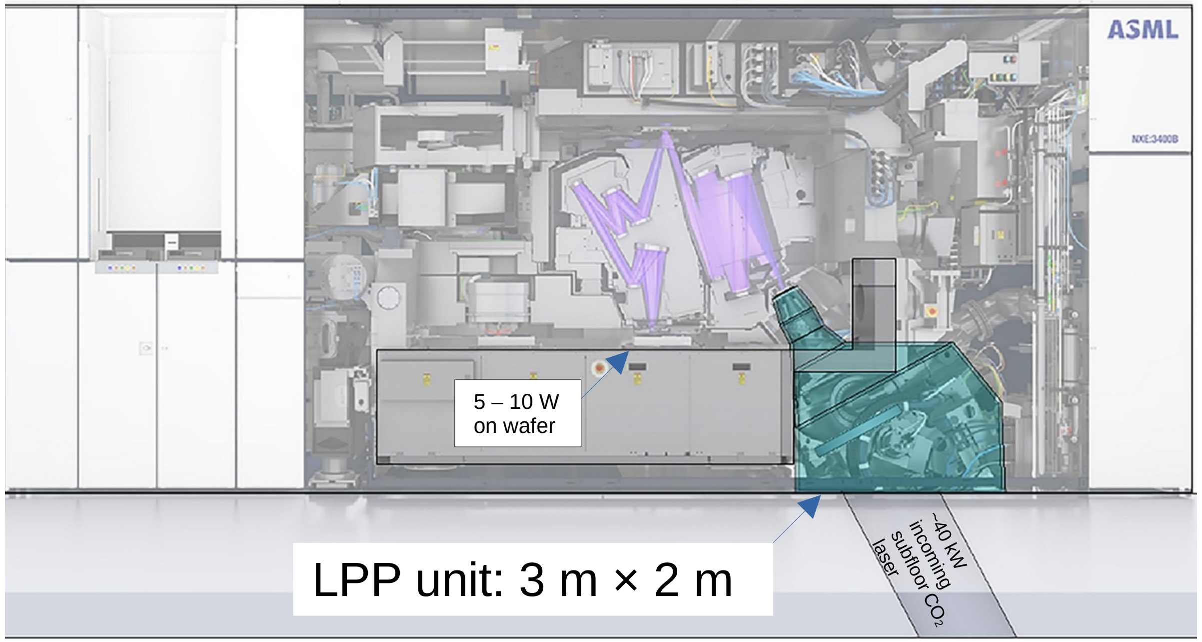
photon wavelength

numerical aperture



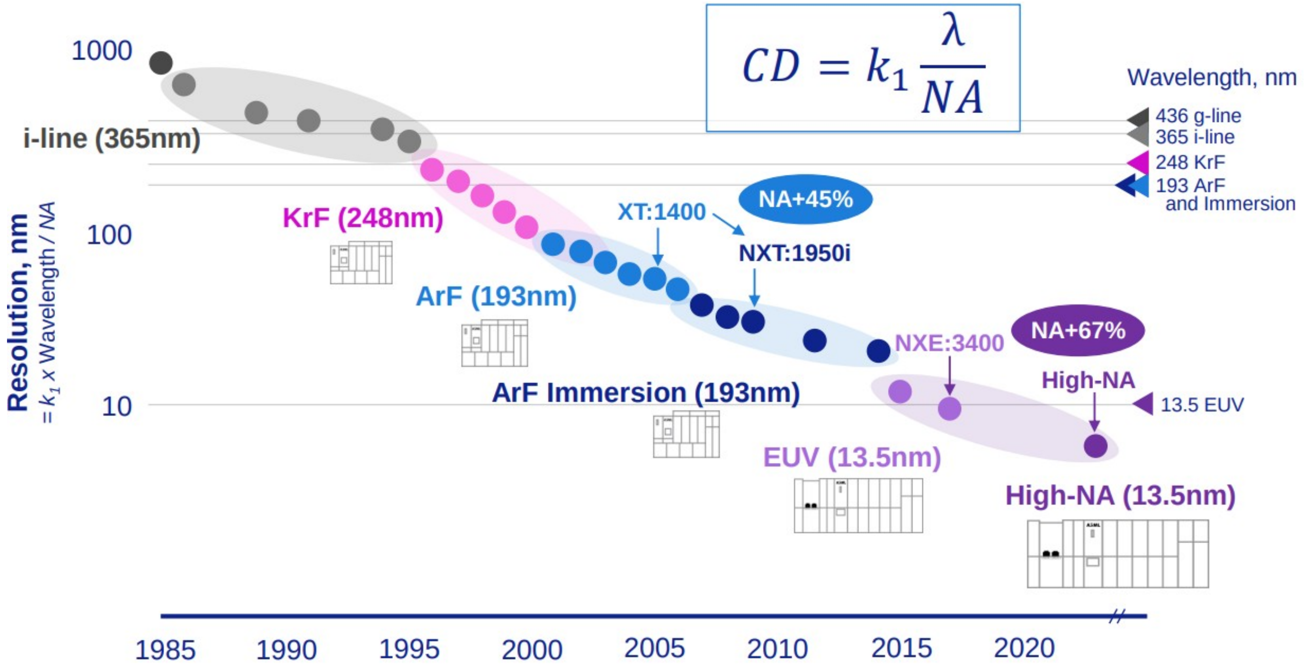
Etching by 193 nm, 1.35 NA compared to 13.5 nm, 0.33 NA

- LPP is the source for EUV litho.
- Droplets of tin plasmatized by a laser.
  - 13.5 nm light emitted during during recombination
  - 50 kHz pulse rate
- Several mirrors transport about 1% of emitted light to wafer



LPP is a point of tension in semiconductor manufacturing

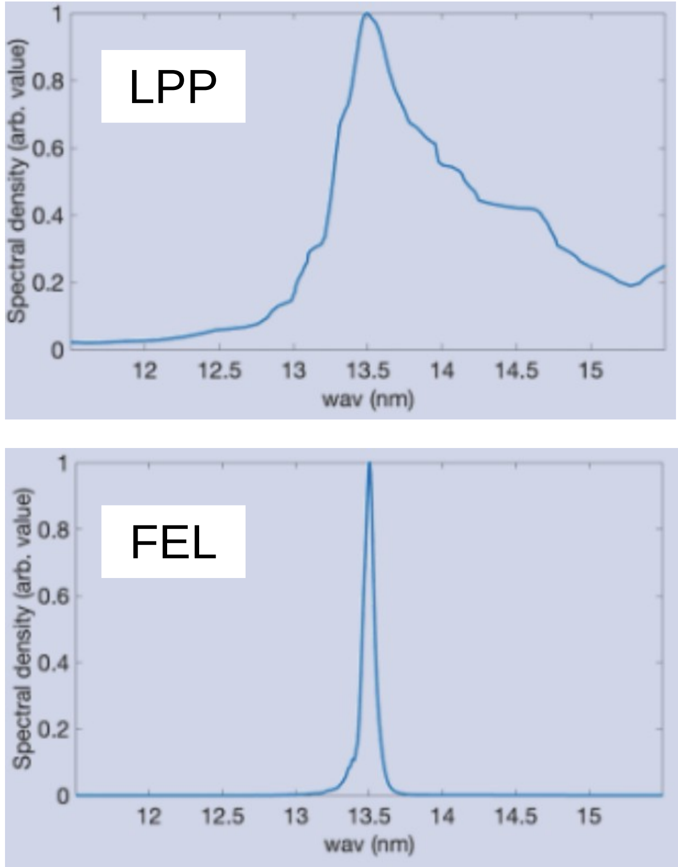
- Tin LPP fixed at 13.5 nm: path to lower R is higher NA
- NA > 0.55 difficult but might allow R = ~5 nm
  - Depth of Focus $\propto$ NA^{-2}, imposing tight optics tolerances
  - 6.7 nm via gadolinium and terbium at exploratory research stage
    - No guarantee 6.7 is optimal for resists
- Tin contamination of optics
- LPP may be strained to deliver sufficient power for High NA EUV and beyond
  - High-NA EUV scanners available as of 2025, not yet proven via widespread adoption



$$CD = k_1 \frac{\lambda}{NA}$$

Accelerator Source Could De-constrain Scanner Engineering

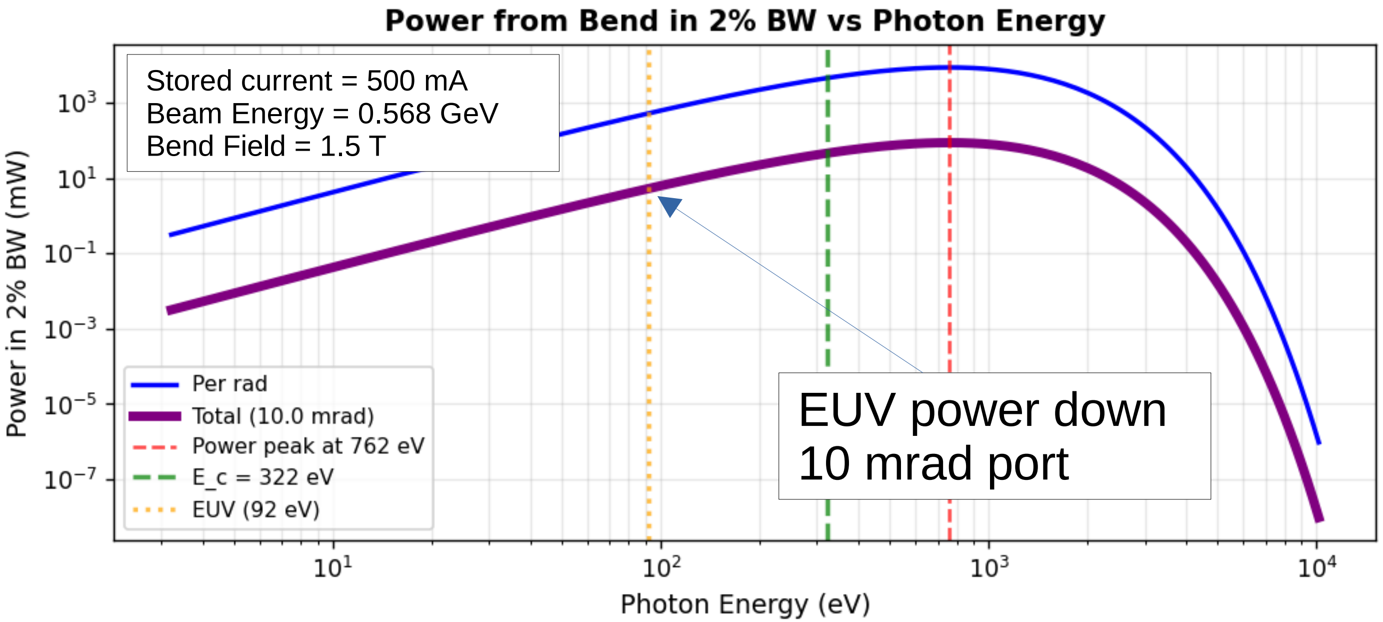
- Accelerator light sources are standard infrastructure at national laboratories
  - High flux spanning THz through hard x-ray
- Photon wavelength could be tailored to optics and resist
  - Smaller features without high NA
- FEL has less out-of-band power: less heat load on optical components
- Polarization can be adjusted varied
- Accelerators built from conventional components subject to fewer supply chain risks.



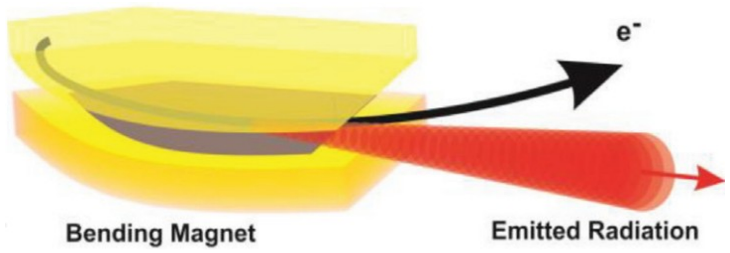
FEL has less out-of-band flux than LPP, reducing heat load on components

Light from a Charged Particle Beam: Bend Radiation

- Relativistic electron beam emits photons along its tangent when bent.
- Total power output is very large, but spectrum is broad.
  - 2% bandwidth @ 13.5 nm down 10 mrad port is ~ 10 mW
  - LPP: 250+ Watts



EUV power down 10 mrad port

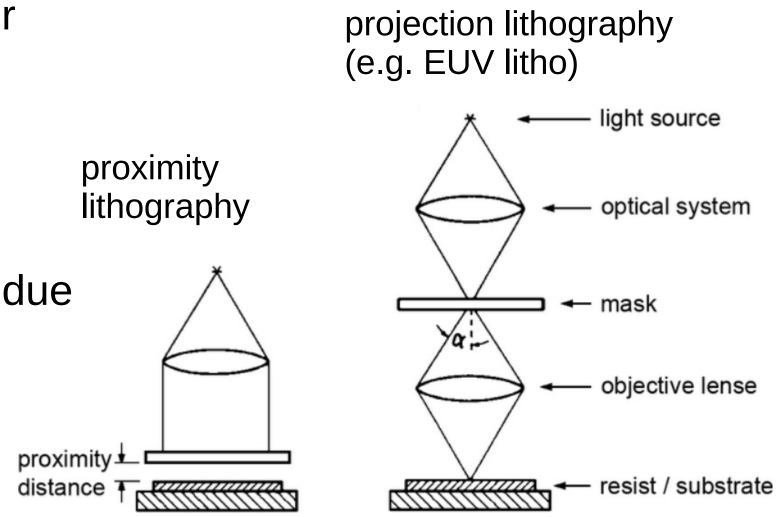


Synchrotrons explored 80s thru 90s for lithography were x-ray proximity lithography systems.

- AURORA, Helios, SORTEC, Nat'l Lab Facilities

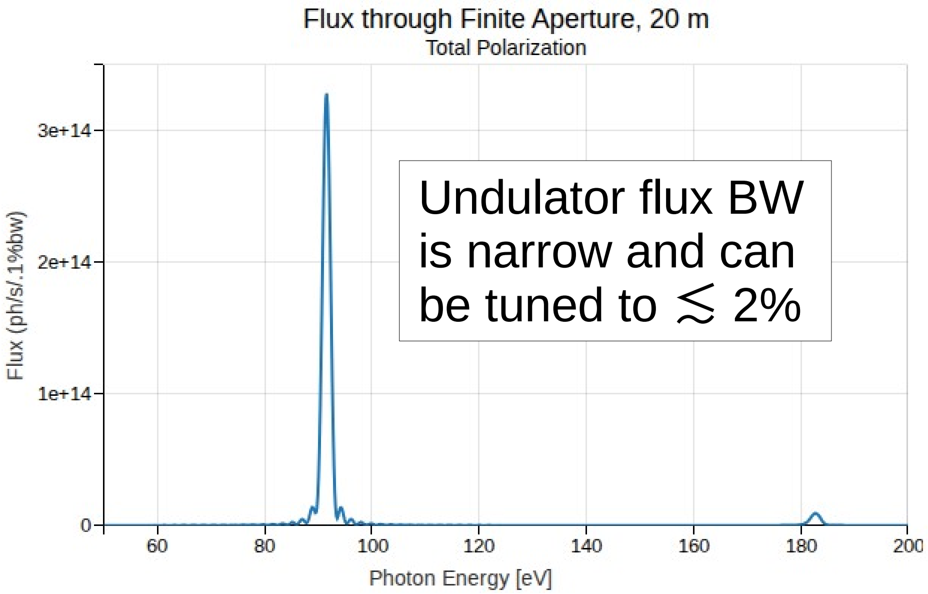
Needs much less light, but disfavored due in part to sensitivity to mask defects.

- proximity litho: 1:1 ratio
- projection litho: 4:1 ratio

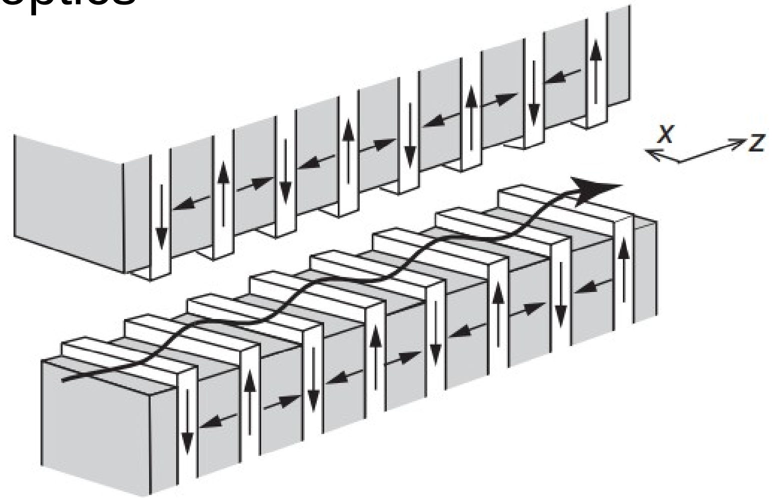


Light from a Charged Particle Beam: Undulator Radiation

- A sequence of bends such that radiation from successive bends adds quadratically.
  - Intensity $\propto N_{pole}^2$
  - Typ. 10^3 times brighter than bend
- Most prevalent technique for generating light from a particle beam
- Never seriously considered for 13.5 nm Lithography
  - Flux still order-of-magnitude weaker than LPP
  - Highly collimated beam difficult match to scanner optics



Undulator flux BW is narrow and can be tuned to $\lesssim$ 2%



photon wavelength

undulator period

undulator B-field

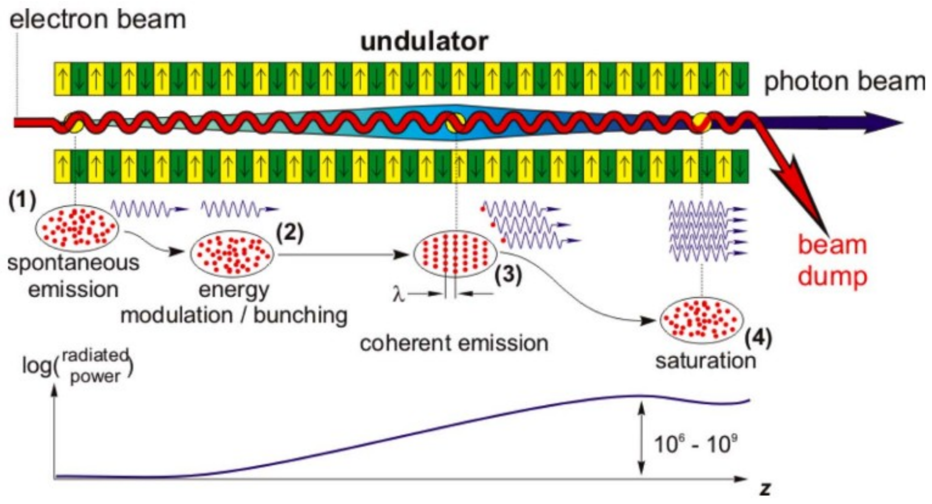
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad K = \frac{eB_0\lambda_u}{2\pi mc}$$

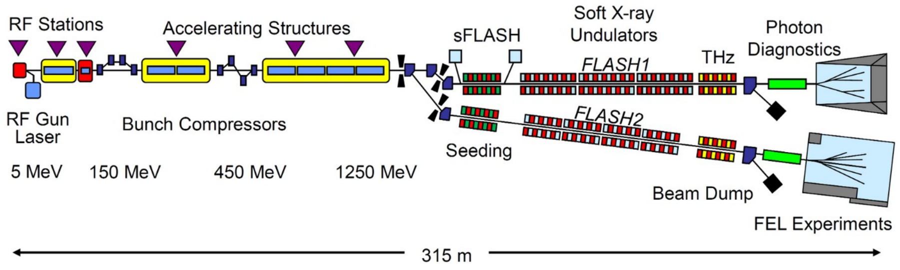
relativistic gamma

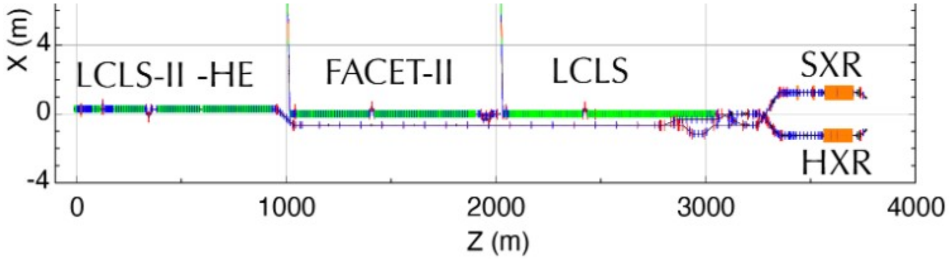
Light from a Charged Particle Beam: Free Electron Laser

- Beam interacts with its own light, such that each bunch radiates coherently
  - Intensity scales with N_e^2
- Small z-p_z area necessary
  - So, linacs, not rings, necessary
- $\lambda \lesssim \lambda_{VUV}$ developed in late 2000s
  - FLASH & LCLS
  - 300 m to > 1 km facilities
  - Several 100 W output
- Late 2000s, FELs shown to be capable of delivering sufficient EUV light, though facility considerations remained a limitation & LPP R&D was underway

	FEL	Ring
σ_p	10^{-4}	10^{-3}
σ_L	< 0.1 mm	1 cm

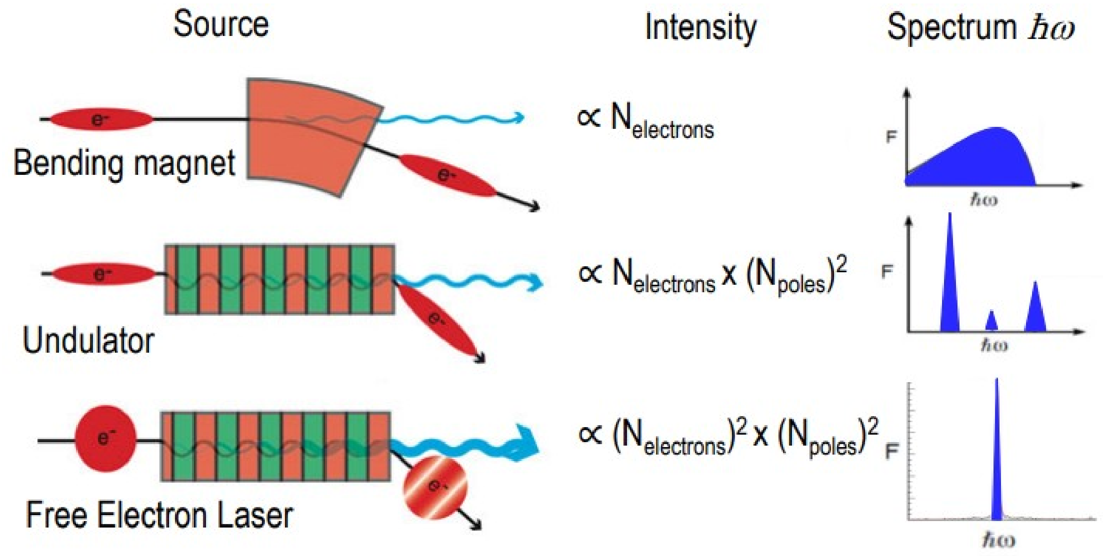


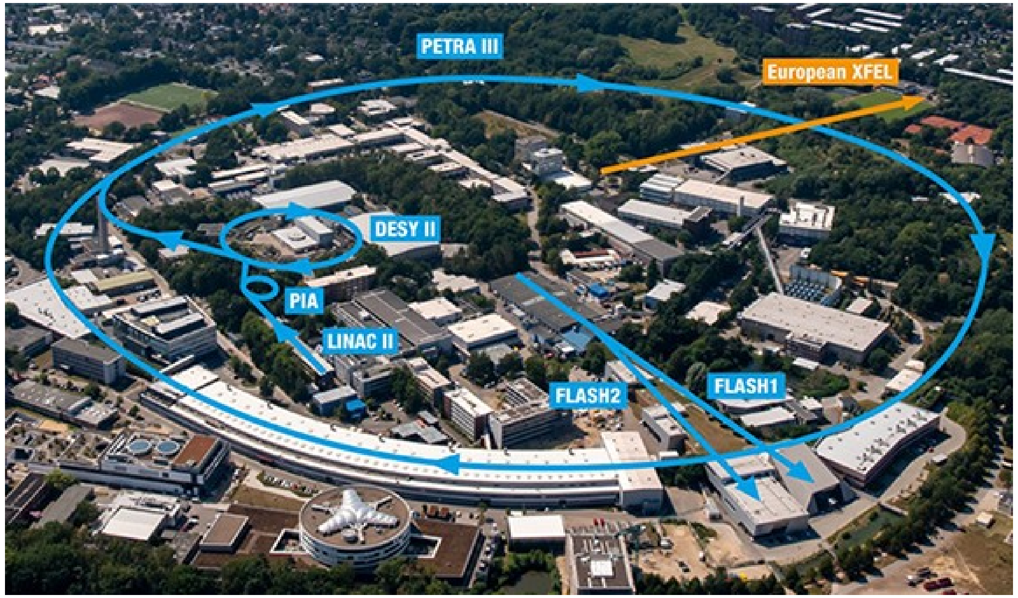




FEL Process Necessary, but Existing Facilities Unsuitable

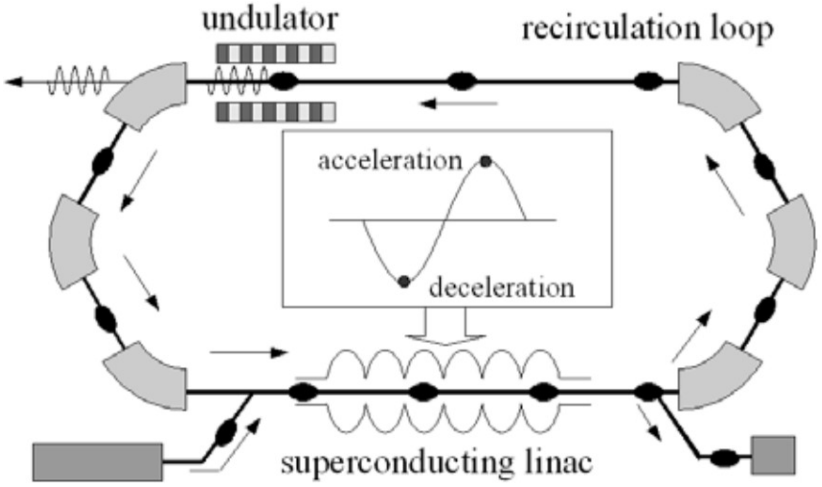
- FEL, or other N_e^2 emission process, necessary to reach kW-level EUV output
  - Example ordinary FEL:
    - ~50 m to reach ~750 MeV
    - ~30 m for undulator
    - < 400 W
- $500M+ capital investment (per lithography scanner)
- Too large and expensive for industrial lithography



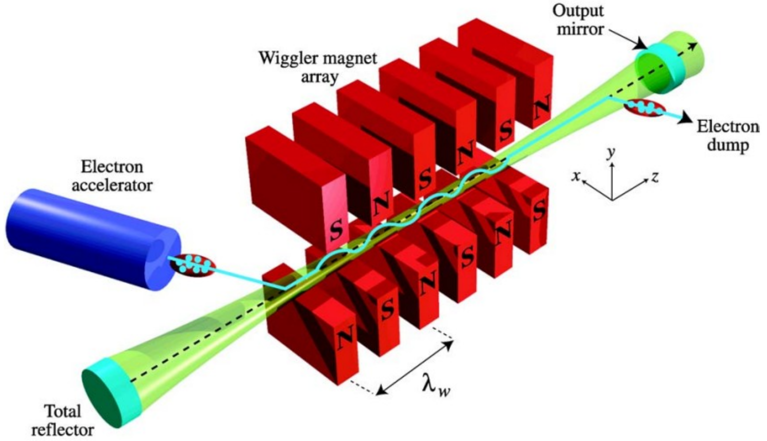


Alternatives to Linac FELs

- Damping ring based FELs limited by Rad. Int., IBS, & FEL-induced energy spread.[1,2]
  - Ring-FEL Intensity ∝ N_b (rather than N_b^2)
- Energy recovery linacs improve efficiency by recovering energy from the spent beam
  - Need to ensure recovery process still works with large energy spread, post-FEL bunches
  - Ungapped beam may excite wakes leading to BBU, thus limiting current and power output
- FEL Oscillators shorten undulator and run below saturation
  - Due to inefficiency of EUV optics, existing machines limited to IR
- Laser wakefield acceleration would replace ~100 m linac with ~1 m plasma channel



Principle of energy recovery linac



Principle of FEL Oscillator

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[1] "Beam dynamics in a storage ring with a free-electron laser," Yunhai Cai, PRSTAB (2025)

[2] "Storage ring operation of the free-electron laser: The amplifier," A. Renieri, Nuovo Cimento B (1979)

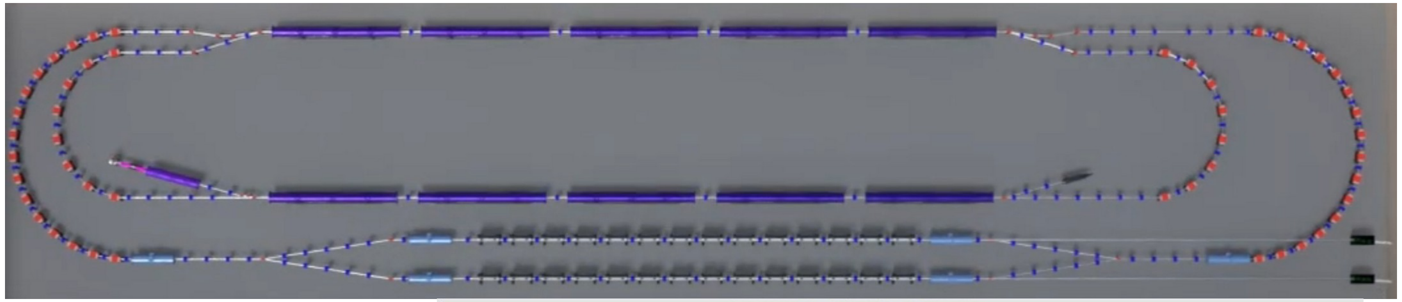
Disclaimer

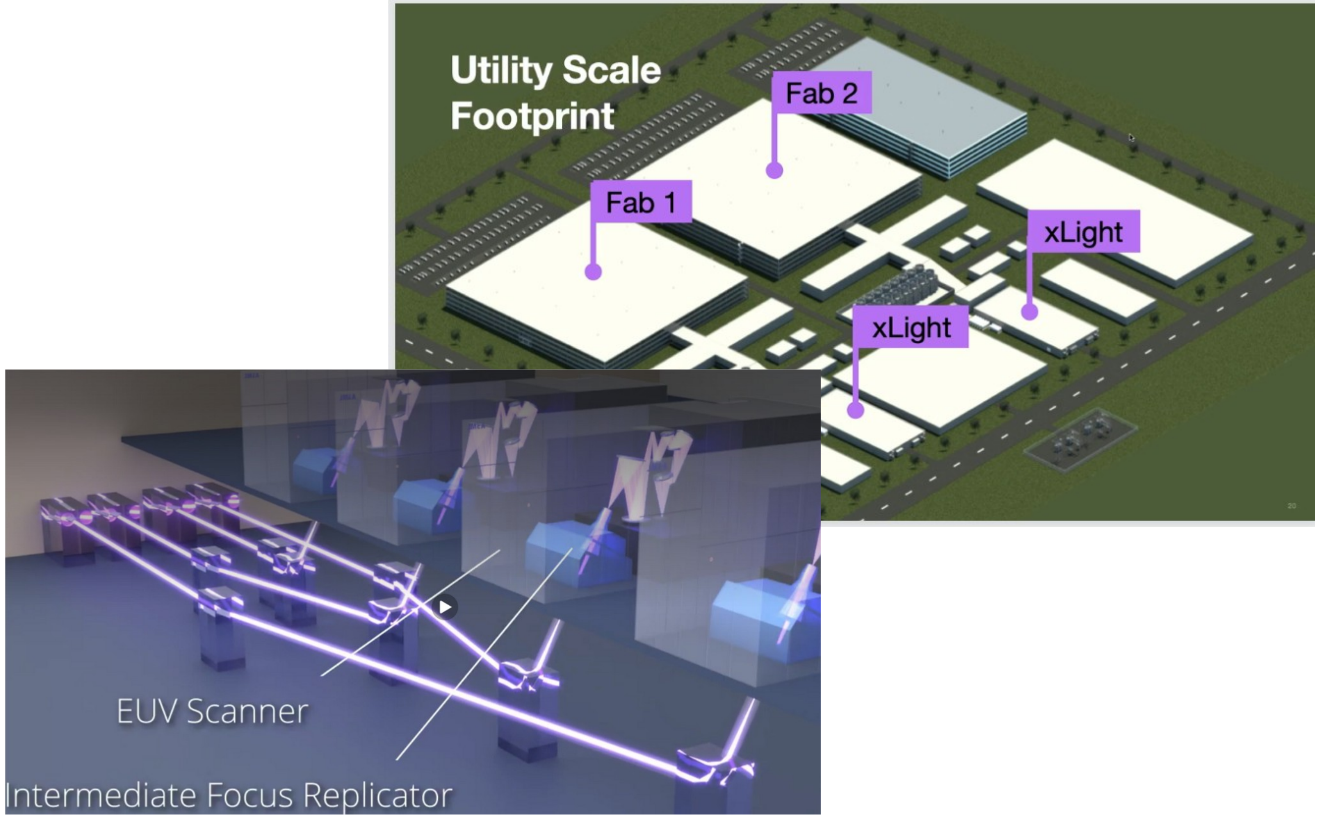
- **We reached out to the several companies that have announced that they are pursuing an accelerator-based light source for lithography.**
- **I have no ties to any of the companies I'll be discussing today, though SLAC might.**
- **I have no privileged information about mentioned companies.**
- **Each company has been given the opportunity to edit its content.**
- **Images are concept illustrations, not schematics.**

Public information provided by named company in response to survey email. No endorsement by SLAC of any company should be inferred nor should one assume this is a complete list of entities active in this sector.

EUV ERL-FEL Pursued by xLight

- Energy Recovery Linac FEL
  - High technology readiness level
    - Construction of demo at Albany, NY Nanotech Complex (targeting 2028)
- High wall-plug efficiency
  - **ERL**: 2 kW in BW light to 16 scanners for 8 MW wall-plug power
  - **LPP**: 500 W in BW light to 1 scanner for 1 MW wall-plug power
- Each xLight ERL capable of delivering 120 kW (before transport losses)
  - Two accelerators per fab for “2N” availability
- **Challenge**: Interfacing a full-size light-source with chip fabrication facilities
  - "Light as a Service" model for operational autonomy
  - xLight is developing its own light distribution & intermediate focus replicator

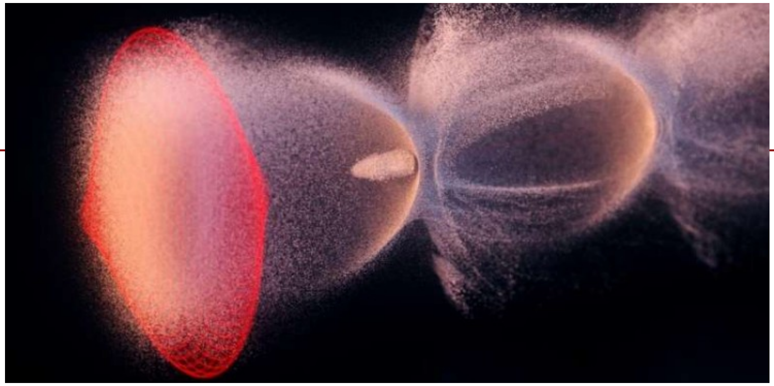




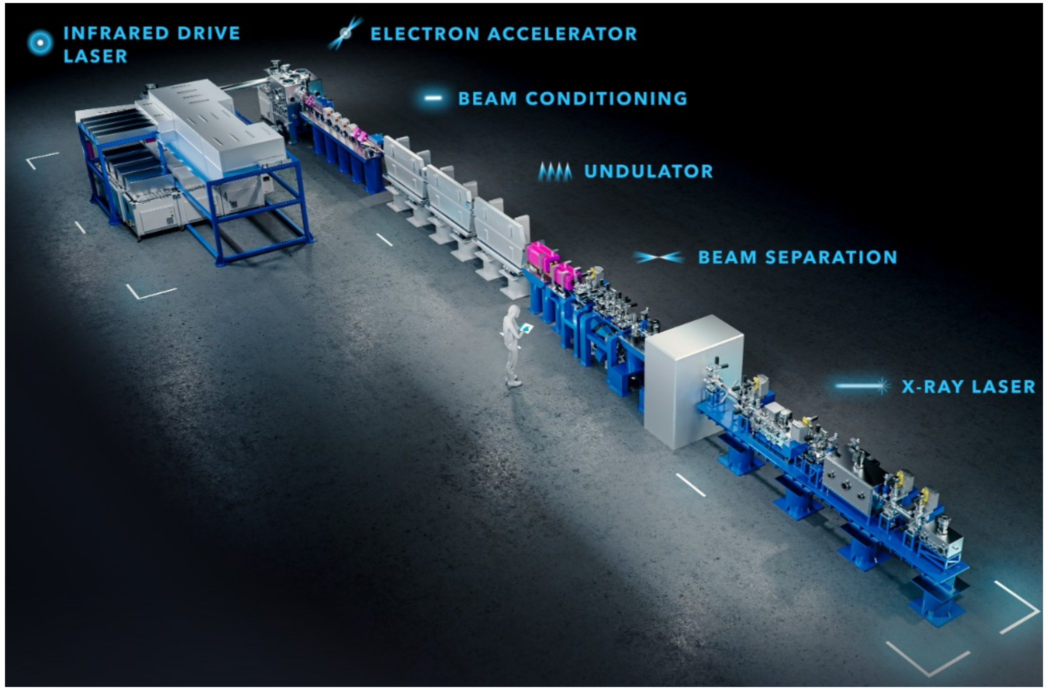
*https://www.xlight.com/company-news/xlight-signs-150-million-letter-of-intent-with-the-us-department-of-commerce

LPA-FEL Pursued by Tau Systems

- Tau Systems markets a LPA source for radiation testing
- Investigating a LPA-FEL for semiconductor lithography
- LPA gradients are a few GeV / meter
  - Compare to SCRF 20 MV/m
  - Avoids the need for cryo plant
- Recent experiments* (at LBNL’s BELLA) demonstrate long-term operation of a LPA-FEL
  - 100 MeV beam driving 4 m undulator → 420 nm light for 8 hours



Laser pulse (red) generates free electrons and a wake bubble in a gas. Electrons are then accelerated at high gradient by the plasma wake.



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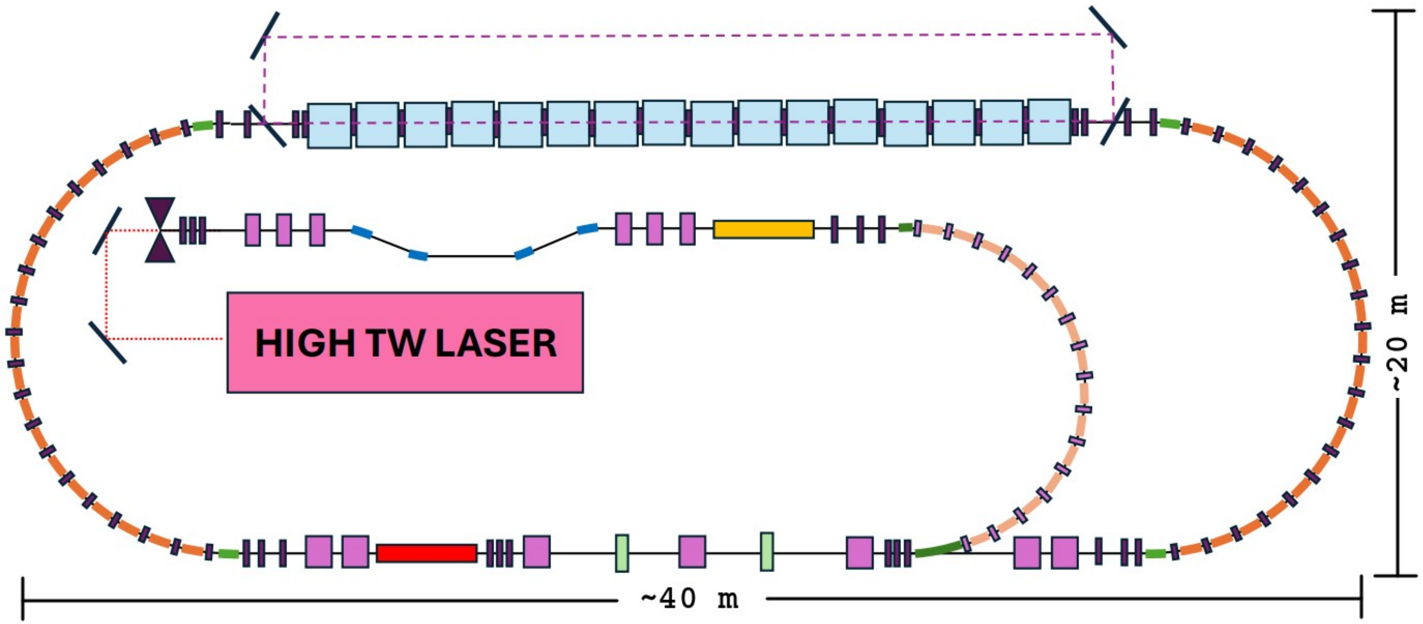
*”Over 8 hours of continuous operation of a free-electron laser driven by a laser-plasma accelerator”, F. Kohrell, et. al. (April 2026) 10.1103/z2d3-bhyt

EUV FEL Oscillator Investigated by Inversion Semiconductor

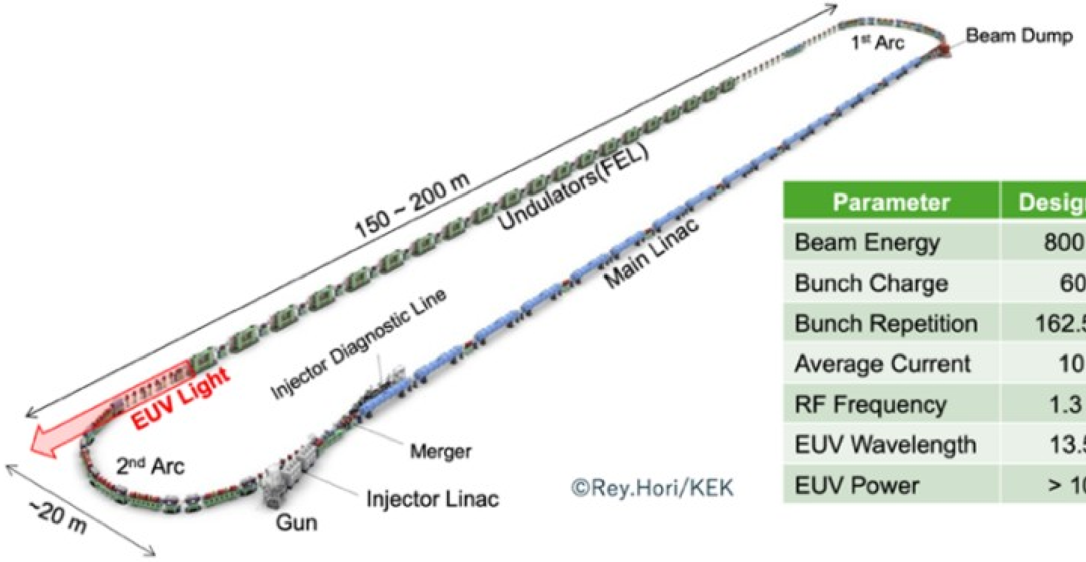
- Inversion Semiconductor* explores accelerator-based solutions for the semiconductor industry
- One investigation is a medium-gain EUV FEL oscillator built around a compact damping ring
  - Laser wakefield injection
  - 1.25 GeV
  - Medium gain FEL, ~20x per pass
  - Each source driving 1-4 scanners
  - Scaling towards >1 kW output and high efficiency at 13.5 nm
- Understanding equilibrium energy spread and transients in an FEL oscillator is a key research topic



*https://www.inversionsemi.com/

ERL EUV-FEL at KEK

- ERL EUV-FEL concept developed at KEK*
  - 10 kW (up to 35 kW) @ 13.5 nm
  - Extensible to 6.7 nm “Beyond EUV”
- PoC underway at KEK’s cERL
- FEL process increases energy spread 3x, where upon energy is recycled into fresh bunches.
- 0.7 MW per 1 kW EUV
  - Cryo is dominant consumer of wall-plug power
- $400m to build (for 10 kW)
- $40M/year to operate
- Compare to LPP (for 1 kW):
  - $80M to build
  - $60M / year to operate
    - Mirror replacement from tin-contamination



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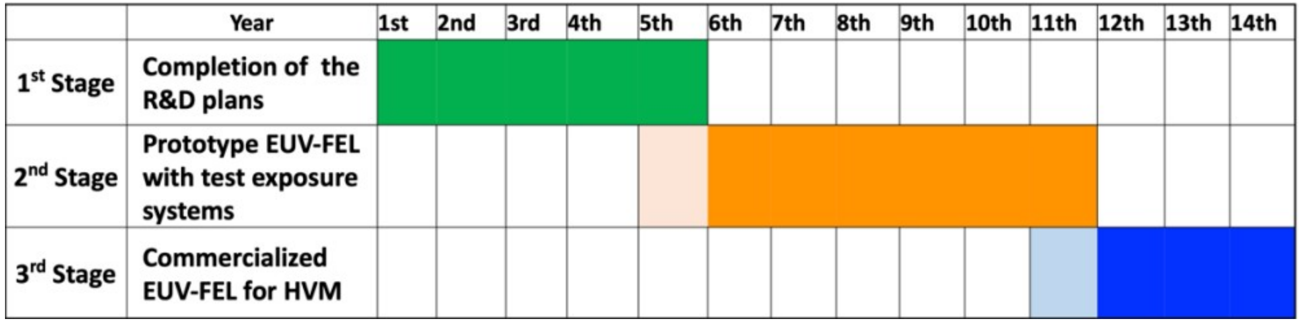
Parameter	Design value
Beam Energy	800 MeV
Bunch Charge	60 pC
Bunch Repetition	162.5 MHz
Average Current	10 mA
RF Frequency	1.3 GHz
EUV Wavelength	13.5 nm
EUV Power	> 10 kW



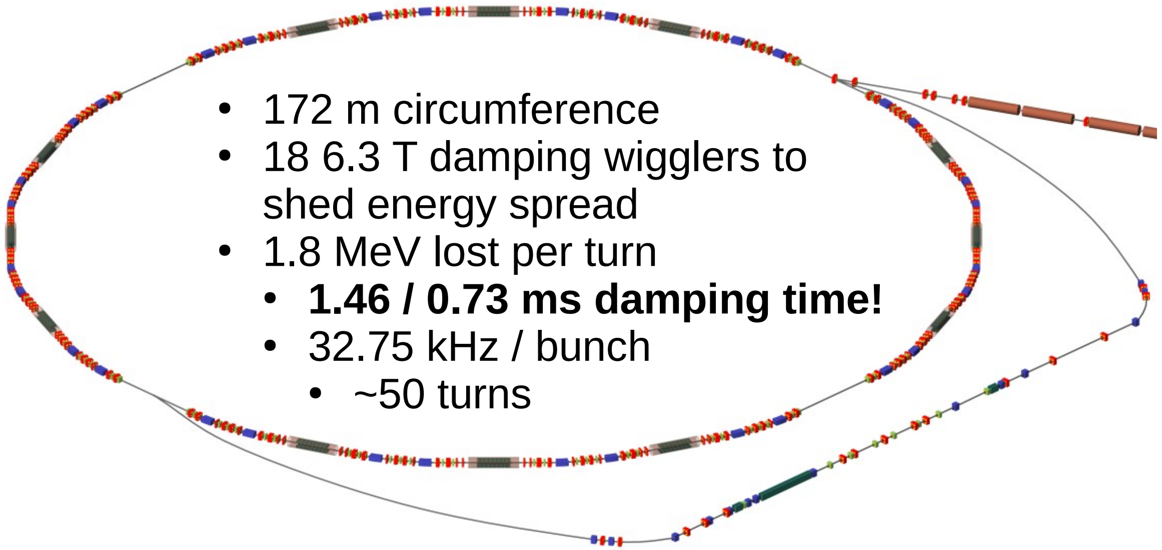
	Year	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th
1st Stage	Completion of the R&D plans	🟩	🟩	🟩	🟩	🟩									
2nd Stage	Prototype EUV-FEL with test exposure systems					▨	🟧	🟧	🟧	🟧	🟧	🟧			
3rd Stage	Commercialized EUV-FEL for HVM											▨	🟦	🟦	🟦

KEK’s possible timeline for realizing their EUV-FEL light source for lithography

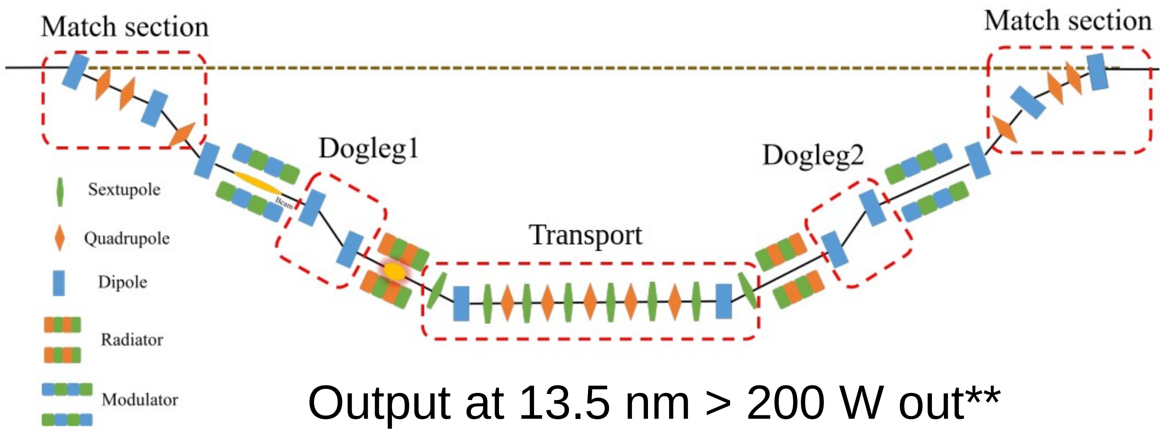
“Research and development of the EUV-FEL light source for lithography,” N. Nakamura, et. al., Photomask Japan 2024

Light Source Efforts at Chinese laboratories

- China has a > $100B R&D effort around semiconductor manufacturing which includes light sources
  - Investigations include ring-based FELs and steady-state microbunching
- Wiggler-dominated ring with bypass line FEL.*, **
  - Angular Dispersion Microbunching, partially reversible
    - Needs low ε_y and fast damping of σ_p
- Needs 6 MHz very stable kicker
- Steady State Microbunching (next slide)



- 172 m circumference
- 18 6.3 T damping wigglers to shed energy spread
- 1.8 MeV lost per turn
  - **1.46 / 0.73 ms damping time!**
  - 32.75 kHz / bunch
    - ~50 turns



Output at 13.5 nm > 200 W out**

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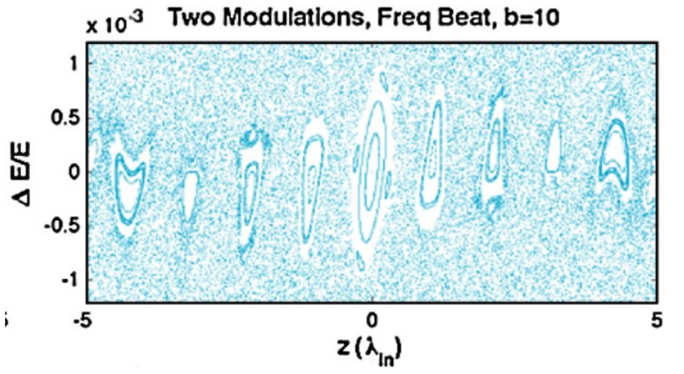
*"A Storage Ring Based Free-Electron Laser for Generating Ultrashort Coherent EUV and X-ray Radiation," C. Feng, Z. Zhao, Nat. Sci. Rpt. (2017).

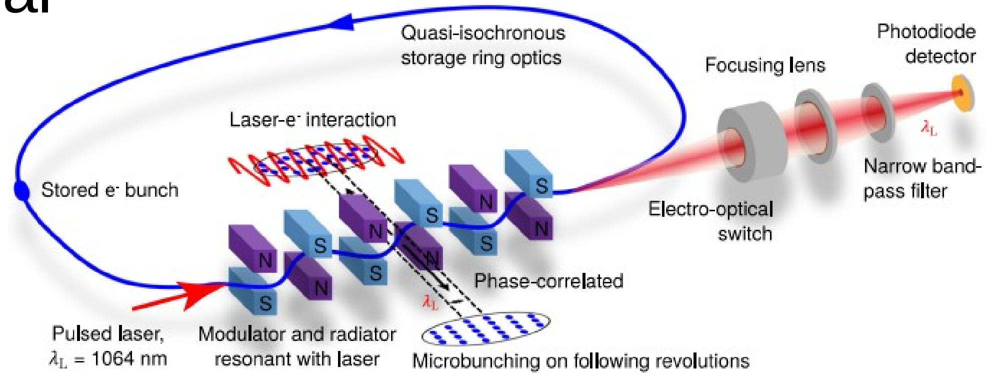
**"Lattice design of a storage-ring-based light source for generating high-power fully coherent EUV radiation," Yu-Jie Lu, et. al., https://arxiv.org/abs/2511.04382 (2025)

Steady-State Microbunching

- SSMB: Secondary longitudinal focusing system bunches the beam ~ λ_{photon}
  - May be paired with reversible compression
  - Like FELs, intensity $\propto N_e^2$
  - Concept in 2010, currently at experimental PoC
  - China’s program includes several SSMB studies
    - MLS PoC participant, Echo SSMB, longitudinal focusing theory
- High current spoils microbunching bunching
  - Needs very weak bunches ~ 500 fC
- A conventional RF ring is already sparsely populated, so 500 fC / bunch is very little current ∴ low power



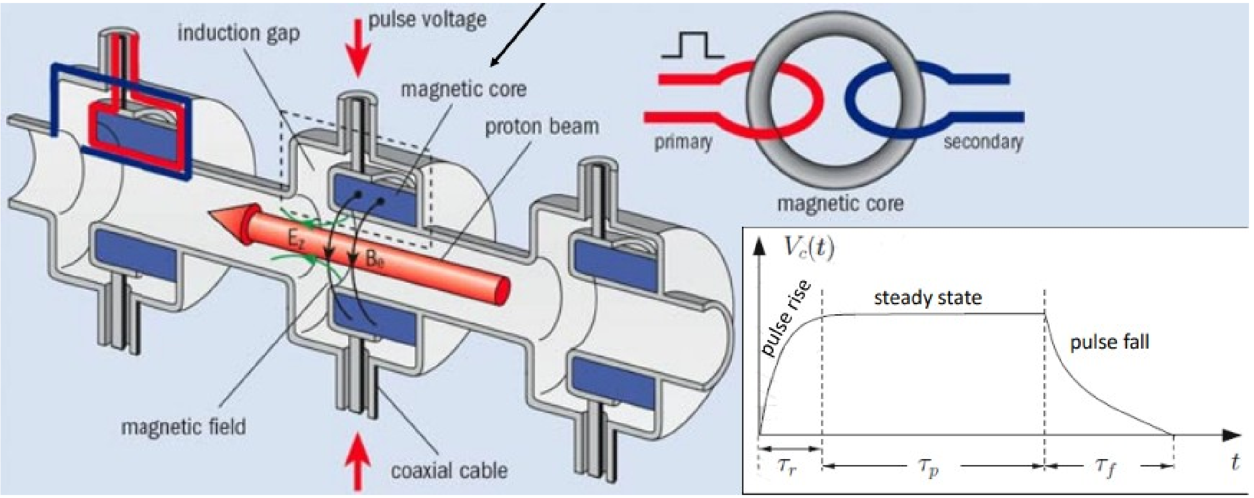
Simulated z-p_z phase space with optical microbunching

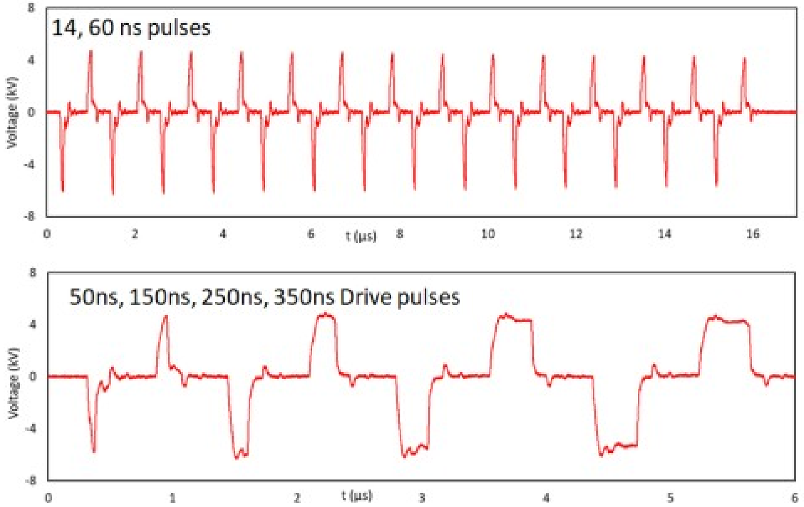


Optical SSMB Proof of Concept at Metrology Light Source in Berlin

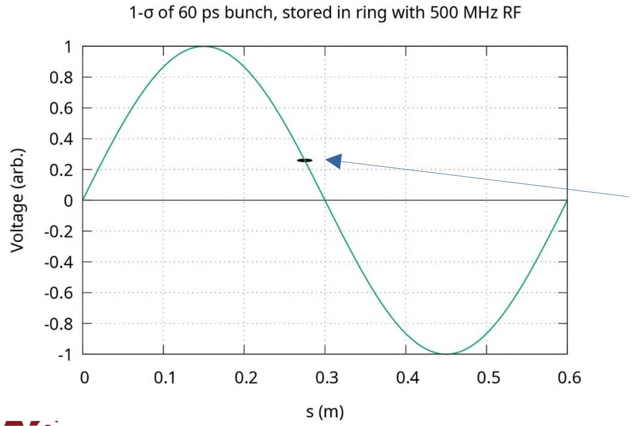
SSMB is a Potential Application of SLAC's Continuous Beams Research

- Recent developments at LLNL in active-reset induction cells raise the possibility of a unbunched electron storage ring.
  - High voltages & 10s ns reset
- Unbunched beam has a peak current 20x lower than a bunched beam of the same current
  - Mitigates: IBS, Touschek, Heating, Top-off
- A high average current, low peak current e- beam could be microbunched for coherent generation of EUV light.





Disadvantage of RF: ring is mostly empty



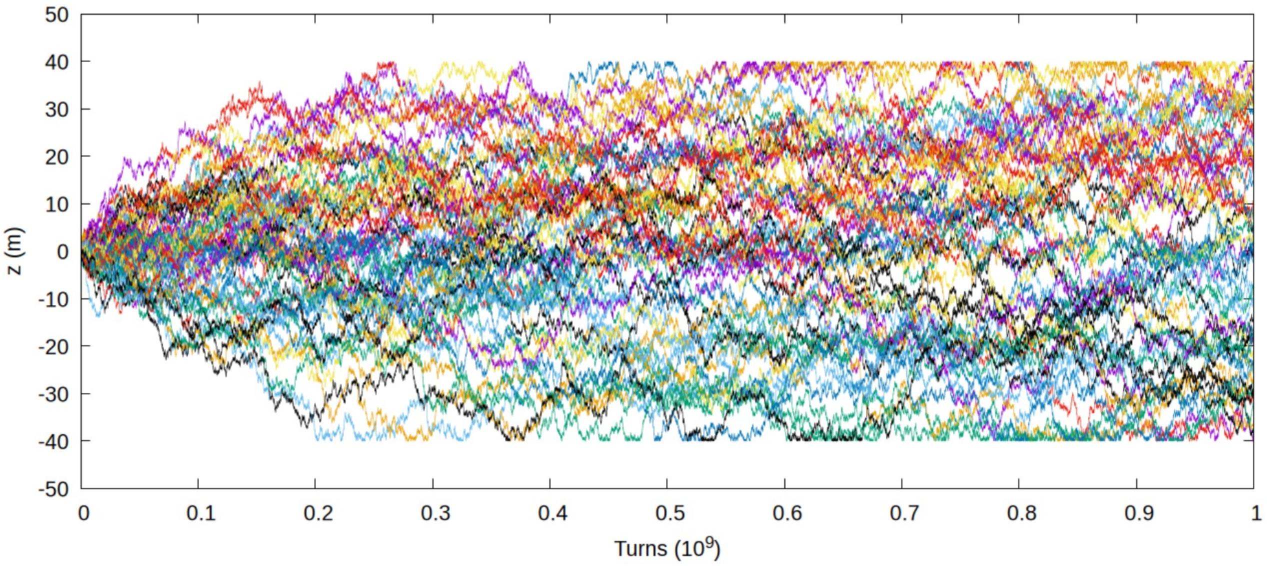
1-σ of bunch drawn to scale. Current stored only in ~3% of the RF wave

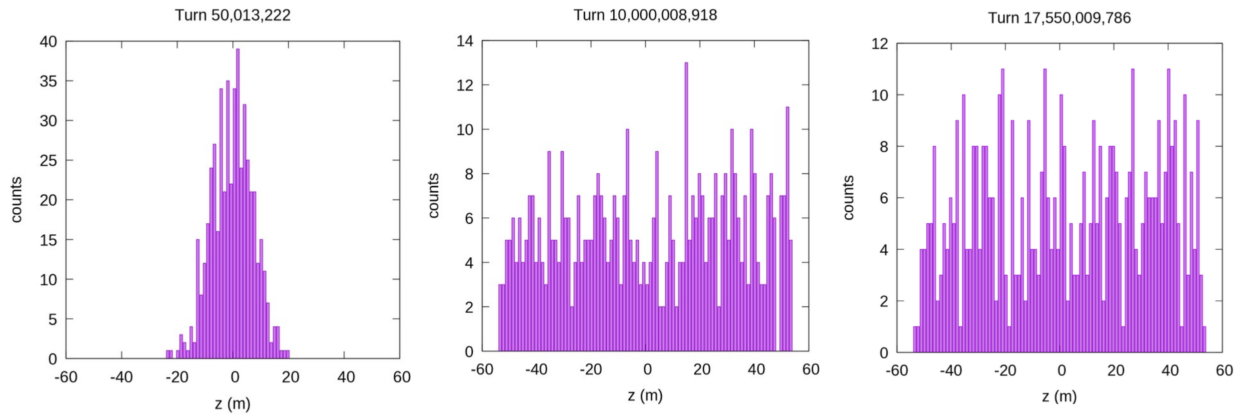
Modeling single particle dynamics in an unbunched electron ring

- RF replaced by Induction Cell

$$M_{\mathrm{IC}} = \mathbf{I} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \Delta E \end{pmatrix} \qquad \Delta E = \begin{cases} U_0 & \text{if } |t| < t_0 \\ U_0 + E_{\mathrm{barrier}} & \text{if } t > t_0 \\ U_0 - E_{\mathrm{barrier}} & \text{if } t < -t_0 \end{cases}$$

- z-p_z dynamics occur on 10^8 turn scales
  - Full dynamics (Bmad): 25 min/MTturn
  - Simple z-p_z tracker: 2.6 s / MTurn
- Particles subject to damping and excitation from photon emission
- Particles random walk (diffuse) relative to reference particle





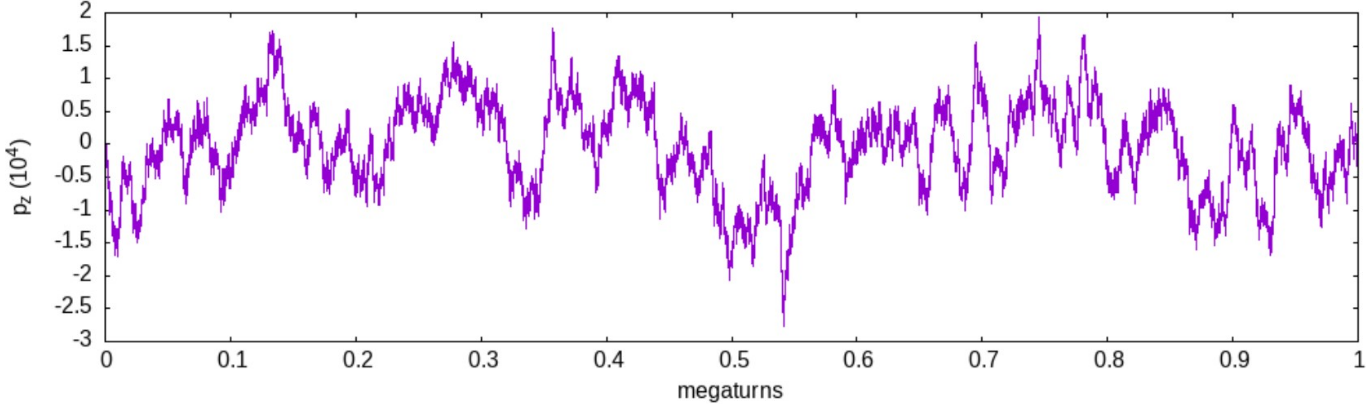
p_z Can be Understood using Radiation Integrals

- Test 1: Energy spread from photon emission
- Track for 100M turns (40 seconds of beam time) and calculate std. dev. of pz

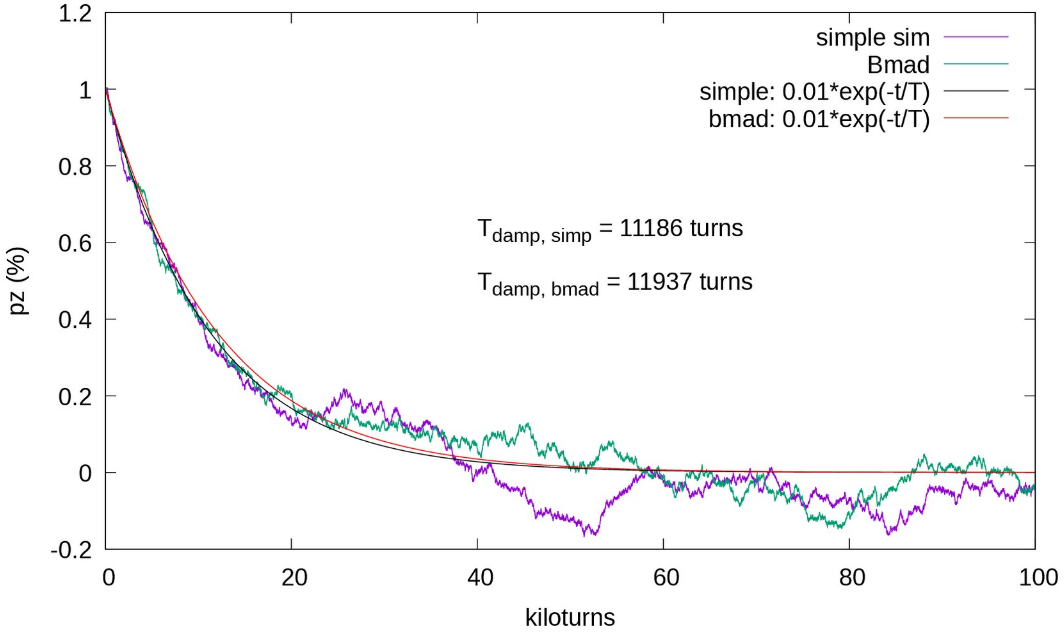
Test #	$\sqrt{\langle p_z^2 \rangle}$
1	$6.22\ 10^{-4}$
2	$6.20\ 10^{-4}$
3	$6.26\ 10^{-4}$
4	$6.32\ 10^{-4}$
Rad. Int.	$6.22\ 10^{-4}$

Std. dev of pz over 100M turns, along with rad int calculation on full lattice model. Evidence that damping and fluctuations are modeled correctly in simple code.

p_z vs turn from simple sim. Used to calculate $\sigma_p^2 = \langle p_z^2 \rangle$

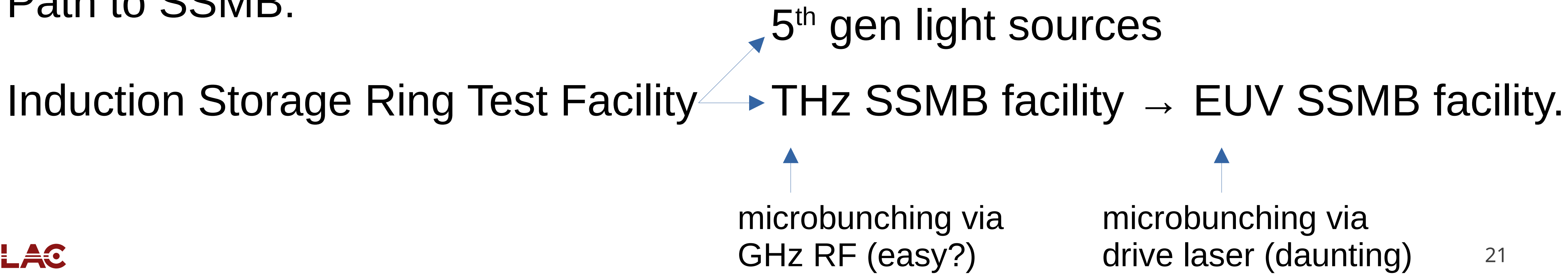


- Test 2: Give particle initial 1% pz kick, track and calculate damping time. Track with both full dynamics Bmad simulation & simple simulation.
- Fit exponential decay to pz vs. turn and compare decay time



Novel Challenges to Understanding Unbunched, Stored Electron Beams (TUP2345)

- Modeling challenges: longitudinal dynamics are very slow, occuring on time scales of 10^9 turns
- Conventional BPMs are blind to DC beams
  - Capacitative BPMs bandpassed at RF frequency
  - Transformer BPMs bottom out at few kHz
  - → Exploring weak density modulation of unbunched beam
- Unclear how long range wake fields will manifest in a continuous beam
- Ion effects in a continuous, low density particle beam
  - May ultimately limit stored current
- Path to SSMB:



5th gen light sources

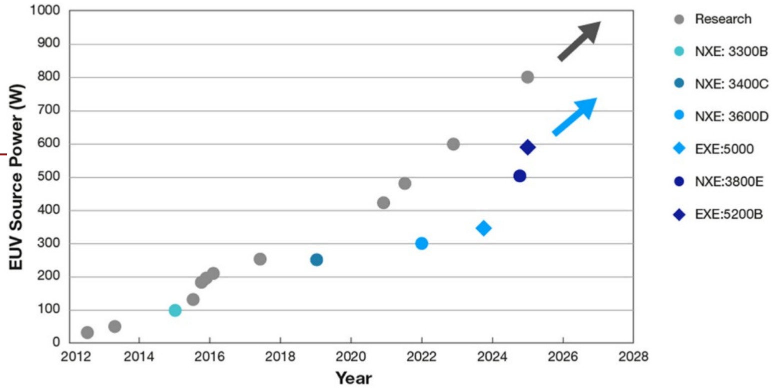
Induction Storage Ring Test Facility → THz SSMB facility → EUV SSMB facility.

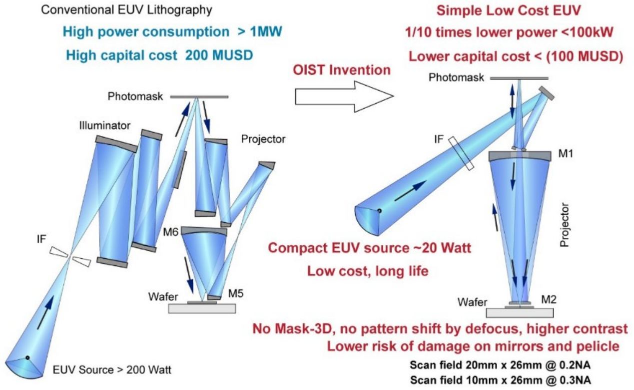
microbunching via GHz RF (easy?)

microbunching via drive laser (daunting)

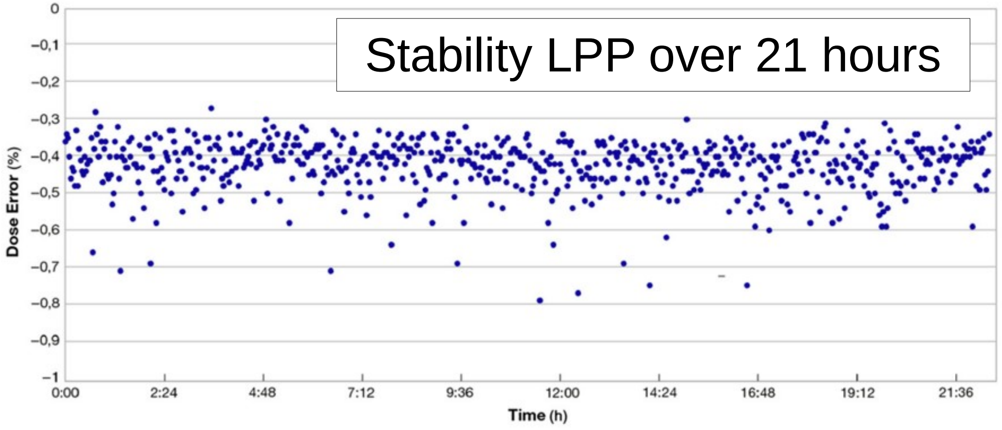
The Broad Picture

- ASML roadmap includes 1 kW LPP source*
  - +60 kHz up from 50 kHz
  - Sophisticated pre-pulse plasmatization
- R&D on radically different, more efficient optics
  - About 30% lost per mirror
- LPP delivers a dose error << 1%
  - FEL process can be unstable
- 13.5 nm is a hard limitation of tin LPP, NA only goes so far
  - Tin alternatives could reach ~6.7 nm, not necessarily ideal for other components





Prof. Tsumoru Shintake, OIST
EUV
0.3 NA
20 W source


Stability LPP over 21 hours

*"Next step in Moore's law: high NA EUV system overview and first imaging and overlay performance," Jan van Schoot, et. al., J. Micro/Nanopattern. Mater. Metrol.

Conclusions

- Light generation for EUV & BEUV litho is a point of tension
- Accelerator-base solutions are a high-uncertainty, high-reward endeavor
  - Highly contested, difficult to calculate parameter space
    - Competing objectives: Capital & Operational costs, footprint, in-bandwidth power, wavelength
  - Semiconductor fabrication with accelerators would require reconsidering aspects of factory design
  - High power and shorter wavelengths would be transformative
  - LPP is entrenched, but NA can only go so far

Image Credits

Diagram of radiation cone from bend magnet: “Fundamentals of Synchrotron Radiation,” Amardeep Bharti and Navdeep Goyal

Diagram of proximity and projection lithography: “Coupling phenomena and scalability of CoFeB/Ru/CoFeB sandwiches,” Nils Wiese

Comparison of ArF and EUV results & Moore’s Law Diagram: “Next step in Moore’s law: high NA EUV system overview and first imaging and overlay performance,” Jan van Schoot, et. al., J. Micro/Nanopattern. Mater. Metrol.

Wavelength of lithography techniques vs. year: ”High-NA EUV Progress and Outlook,” Jan van Schoot

FEL and LPP Bandwidth comparison: “On the Compatibility of Free-Electron Lasers With EUV Scanners,” Christopher N. Anderson

Undulator depiction: “Synchrotron Radiation Sources”, D. Phil Woodruff, doi: 10.1017/9781316995747.003

Principle of ERL Operation: “ENERGY RECOVERY LINACS FOR LIGHT SOURCES,” R. Hajima, DOI: 10.1142/S1793626810000397

Concept illustration of FEL Oscillator: “Free-Electron Lasers Push into New Frontiers,” Stephen V. Benson

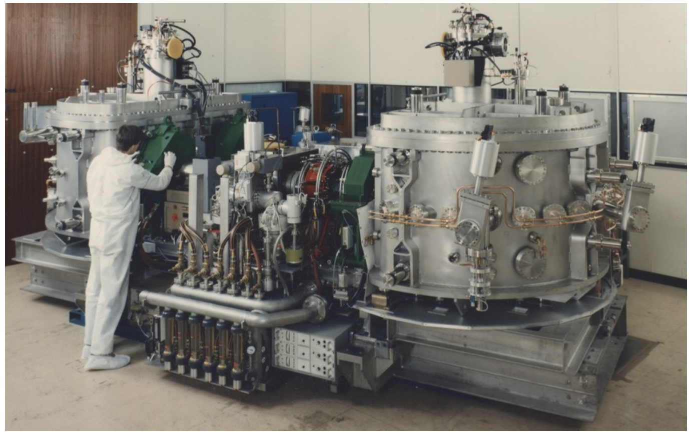
Reduced mirror arrangement for EUV litho: “Can we improve the energy efficiency of EUV lithography?”, T. Shintake. Photomask Japan 2024

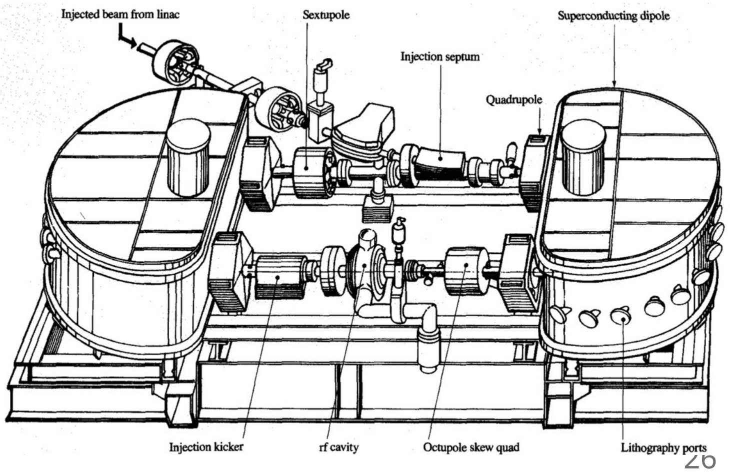
Archive

The following are archived slides not for presentation.

Accelerator-based x-ray proximity lithography research

- 1:1 lenseless proximity “shadow” lithography explored in 80s and 90s. Used accelerator-based sources of incoherent x-ray light.
  - SORTEC, Japan. 80s & 90s. 1 GeV storage ring. 200 mA, 50 hour lifetime. 45.7 m circumference. 500 nm-rad emittance. 1.2 T bend radiation (1.55 nm critical, 6.5 nm peak, 6.37 kW incoherent x-ray power). x-ray lithography experiments.
  - IBM’s x-ray lithography program 80s & 90s*.
    - Utilized bend radiation from NSLS soft X-ray VUV ring.
    - Helios
      - 700 MeV, 10 m circumference, 1 nm soft x-rays. Reliability focus “20 out of 21 shifts”
      - 4.5 T superconducting racetrack
      - ~1 μm-rad emittance
      - Achieved 99% availability
- Challenges: Penumbral blur, mask defects
- Ultimately, x-ray proximity lithography lost out to improvements in optical lithography.





* *X-ray lithography in IBIVI, 1980-1992, the development years*, Alan D. Wilson

Isochronous Arc Assembled from Anti-bend Cells

- One arc of a periodicity 4 isochronous ring shown.
- Arcs are isochronous to 3rd order and mid-arc R_{56} excursions are minimized
- Isochronous condition reduces power requirements from microbunching system
  - GHz RF for THz SSMB
  - Drive laser for EUV SSMB
- Unbunched beam keeps current per microbunch small, mitigating effects that spoil longitudinal phase space