Free-electron lasers: beyond EUV Lithography Insertion

Erik R. Hosler, Obert R. Wood II

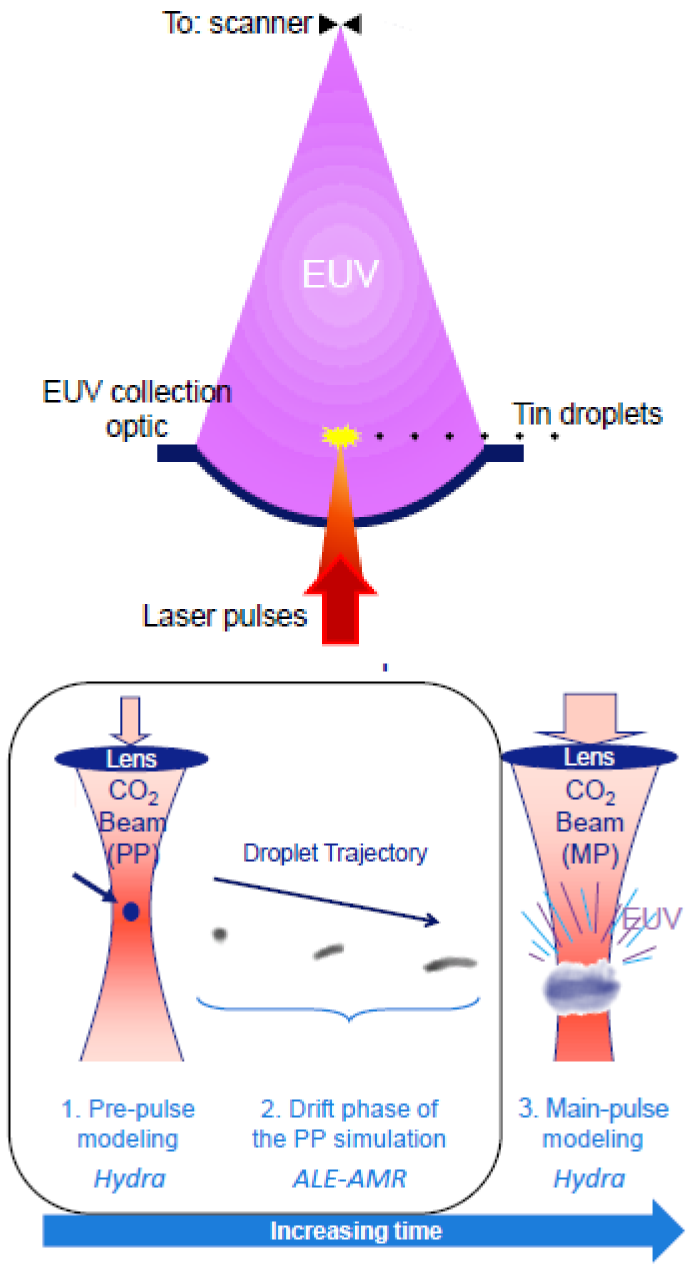
EUV Source for HVM – State of the Art

- Laser-produced plasma source
  - High-power CO_2 laser
  - Sn droplet source
  - Feedback and control systems

- ASML/Cymer
  - 125 W sources deployed to customers
  - ~200 W on test benches

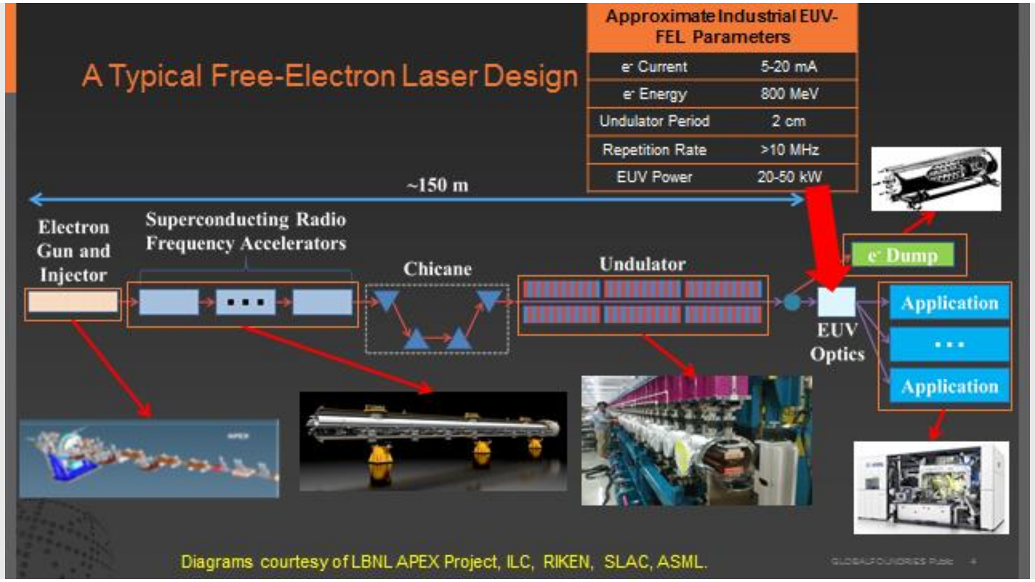
- Gigaphoton
  - Sn debris mitigation strategy, robust drive laser
  - 133 W (in-burst) @ 100 kHz

- ‘When’, not ‘if’
  - Insertion discussed @ 7nm – 2018/2019
  - No longer ‘an exercise’



Pirati, A., et al. SPIE Proc. EUVL, 2016.
Purvis, M., et al. SPIE Proc. EUVL, 2016.
Okazaki,S., et al. ICXRL. 2016.

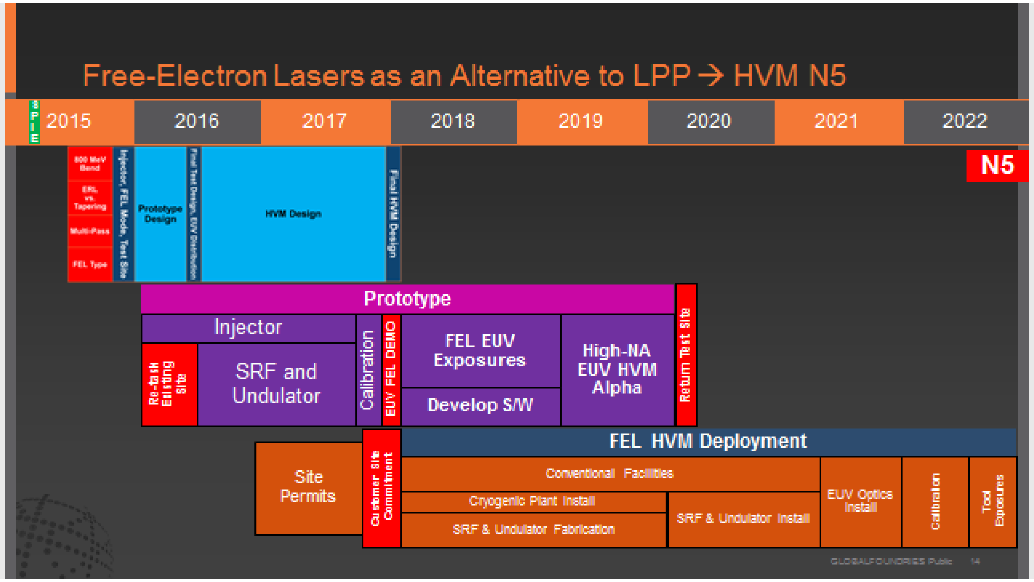
Is there still a case for EUV FELs?
What needs to be done from here?



A Typical Free-Electron Laser Design

Approximate Industrial EUV-FEL Parameters	
e⁻ Current	5-20 mA
e⁻ Energy	800 MeV
Undulator Period	2 cm
Repetition Rate	>10 MHz
EUV Power	20-50 kW

Diagrams courtesy of LBNL APEX Project, ILC, RIKEN, SLAC, ASML.



Free-Electron Lasers as an Alternative to LPP → HVM N5

E.R. Hosler, O.R. Wood, W.A. Barletta, P.J.S. Mangat and M.E Preil, Considerations for a free-electron laser-based extreme-ultraviolet lithography program. Proceedings of SPIE 9422, Extreme Ultraviolet (EUV) Lithography VI. 94220D. 2015.

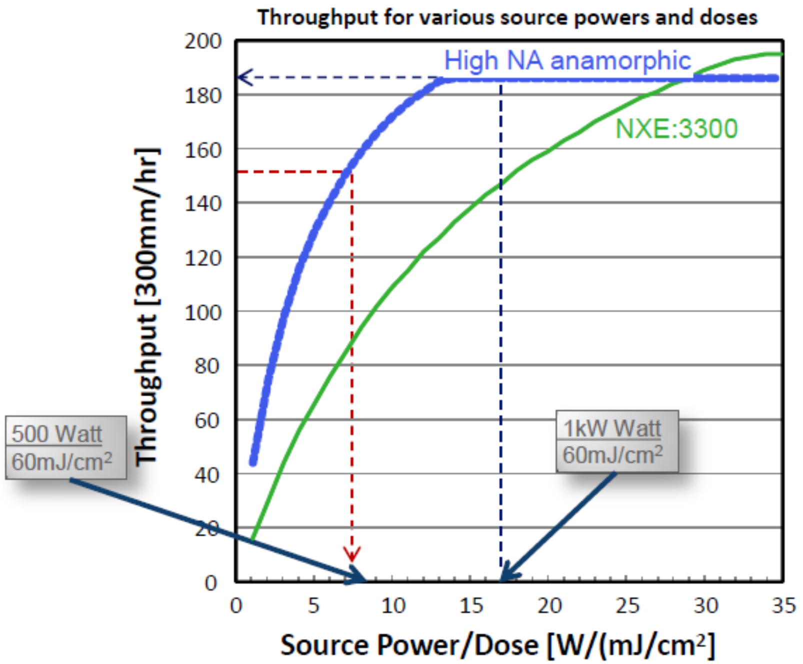
Extreme-Ultraviolet Lithography High-Volume Manufacturing

- EUV for ~~N5~~ ***N3*** and beyond: high-NA or multi-patterning?

- ~~N5~~ ***N3*** lithography requirements[†]
  - ~~5-10+~~ 10+ EUV single exposure layers
  - Dose >50 mJ/cm^2
  - 2k → 5k+ wafer starts per day

- **~~N5~~ *N3* requires an EUV source power ~500→1000 W**
  - High availability/reliability and throughput

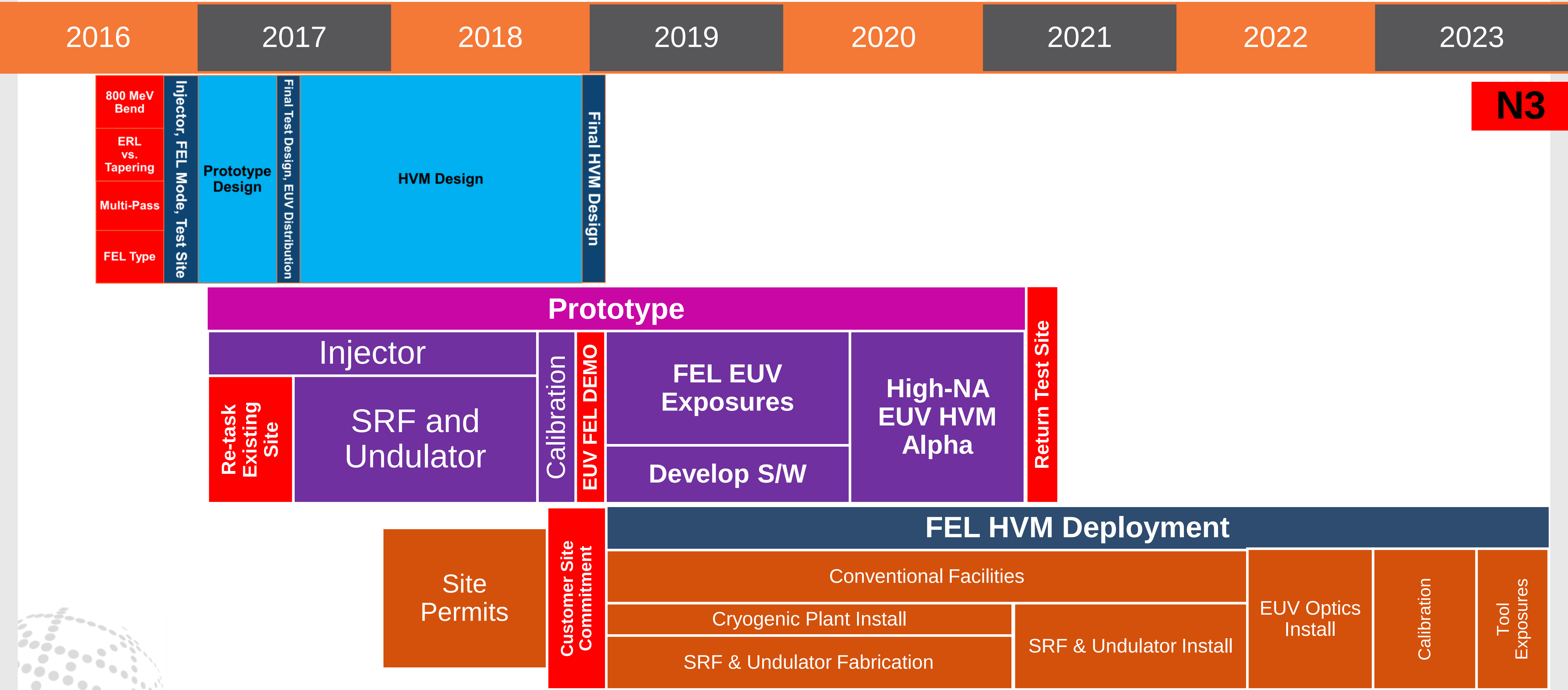
- Free-Electron Lasers (FELs)
  - Potential for deployment by ~~2022-2024~~ ***2024***



High-NA EUV Scanner Throughput

[†] IMEC Technology Roadmap
van Schoot., J., et al. EUVL 2015. Maastricht, Netherlands
Hosler, E.R., et al. SPIE Proc. EUVL. 2015.

Free-Electron Lasers HVM N3



2016 2017 2018 2019 2020 2021 2022 2023

N3

800 MeV Bend

ERL vs. Tapering

Multi-Pass

FEL Type

Injector, FEL Mode, Test Site

Prototype Design

Final Test Design, EUV Distribution

HVM Design

Final HVM Design

Prototype

Injector

Re-task Existing Site

SRF and Undulator

Calibration

EUV FEL DEMO

FEL EUV Exposures

Develop S/W

High-NA EUV HVM Alpha

Return Test Site

Site Permits

Customer Site Commitment

FEL HVM Deployment

Conventional Facilities

Cryogenic Plant Install

SRF & Undulator Fabrication

SRF & Undulator Install

EUV Optics Install

Calibration

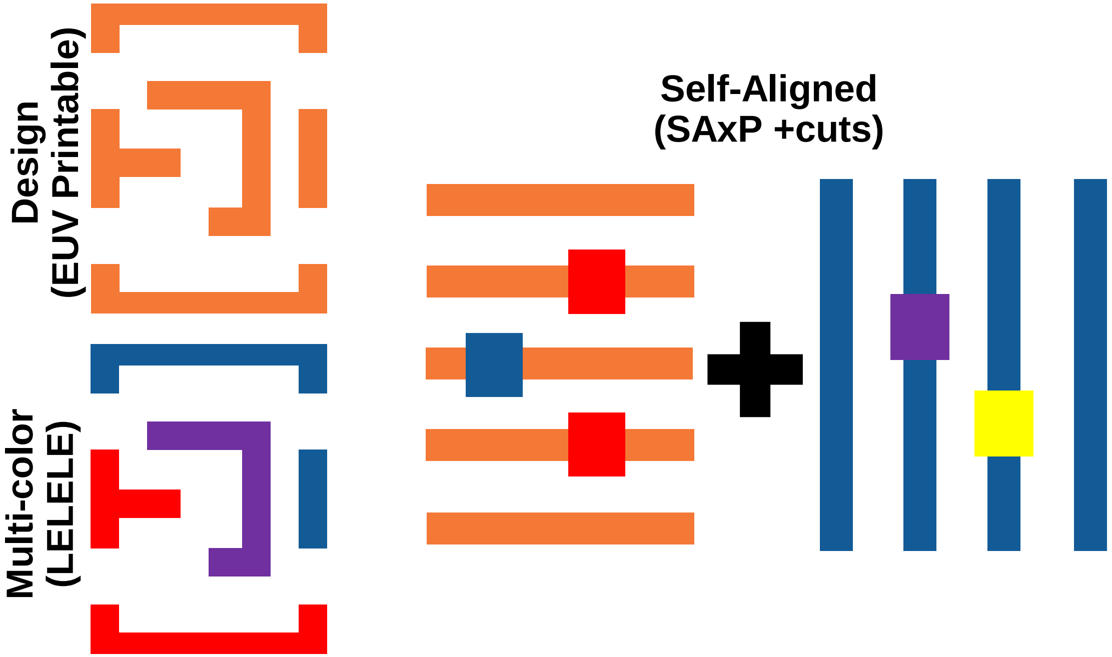
Tool Exposures

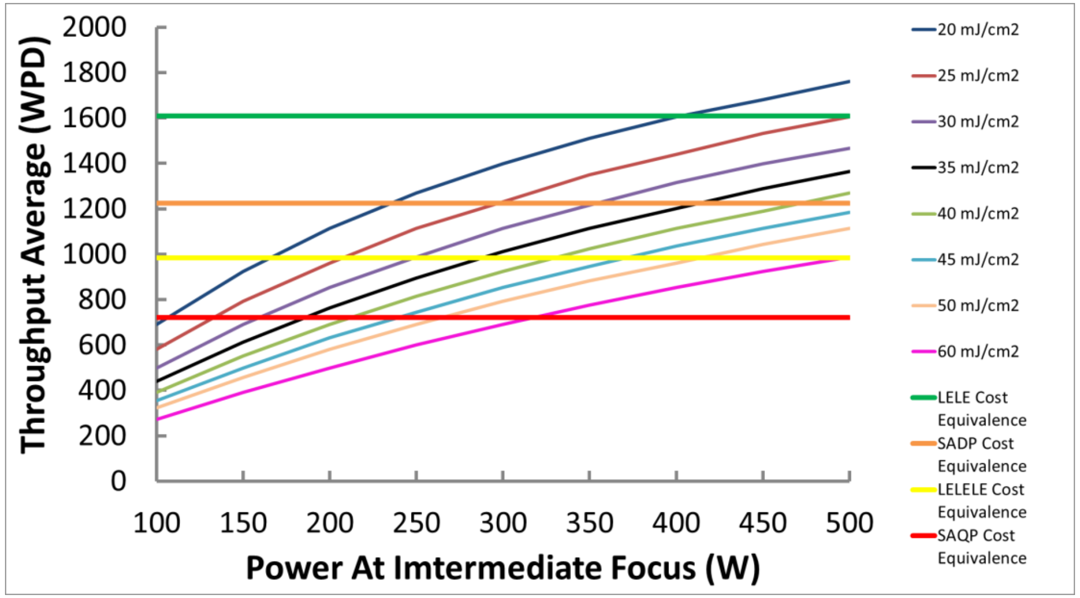
Dose Scaling with Technology and Wafer Throughput

- As target dimensions shrink
  - High-NA option → higher dose
  - NA 0.33 → EUV multi/self-aligned patterning

- Challenge of the middle-of-the-line (MOL)
  - ~2x mask increase per technology generation
    - OVL and Alignment
  - Self-aligned techniques (SAxP) + cuts
    - Design and Process Complexity

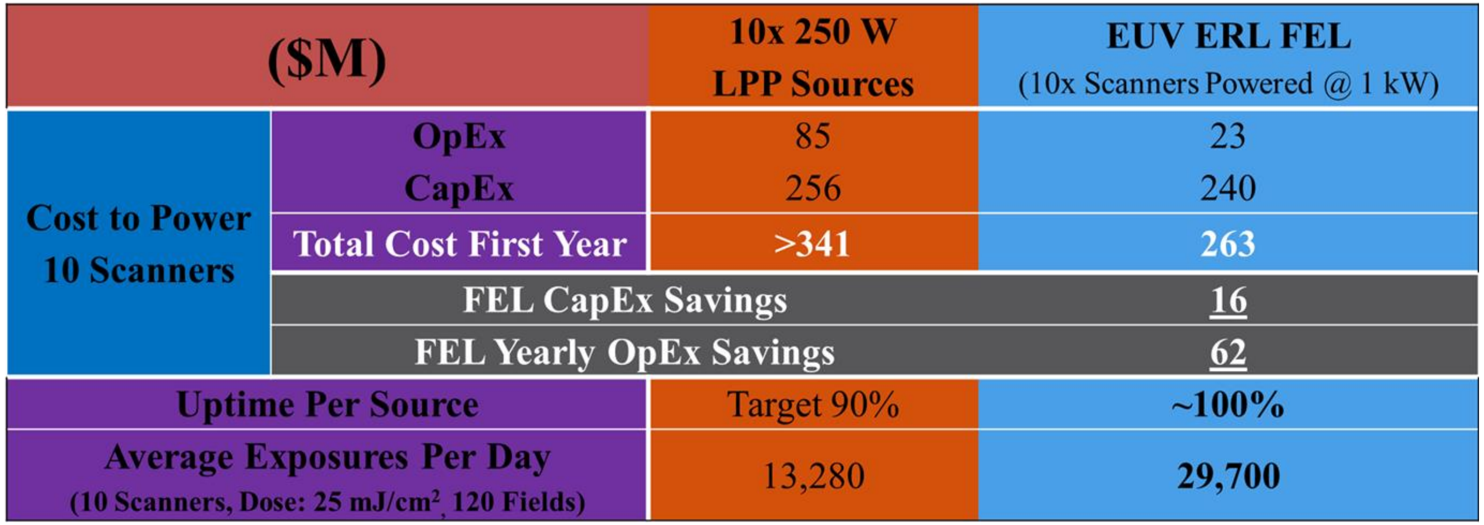
- EUV can reduce the number of cut, contact and via masks
  - Must be cost competitive





The Most Important Thing…

- **Cost!**
  - Lower cost per kW
- An EUV FEL must power multiple scanners simultaneously
- **FEL EUV source must operate with an availability of 100%**
  - 10x 95%...not adequate…
  - **Two FELs must be run simultaneously!**
  - Redundancy of high-risk/low-cost machine components
  - Minimizing stress on long replacement time components
- No debris generation
- Potential for turn-key operation



($M)		**10x 250 W LPP Sources**	**EUV ERL FEL** (10x Scanners Powered @ 1 kW)
Cost to Power 10 Scanners	**OpEx**	85	23
	CapEx	256	240
	Total Cost First Year	**>341**	**263**
	FEL CapEx Savings		**16**
	FEL Yearly OpEx Savings		**62**
Uptime Per Source		Target 90%	**~100%**
Average Exposures Per Day (10 Scanners, Dose: 25 mJ/cm^2, 120 Fields)		13,280	**29,700**

E.R. Hosler, O.R. Wood, W.A. Barletta, P.J.S. Mangat and M.E Preil, Considerations for a free-electron laser-based extreme-ultraviolet lithography program. Proceedings of SPIE 9422, Extreme Ultraviolet (EUV) Lithography VI. 94220D. 2015.

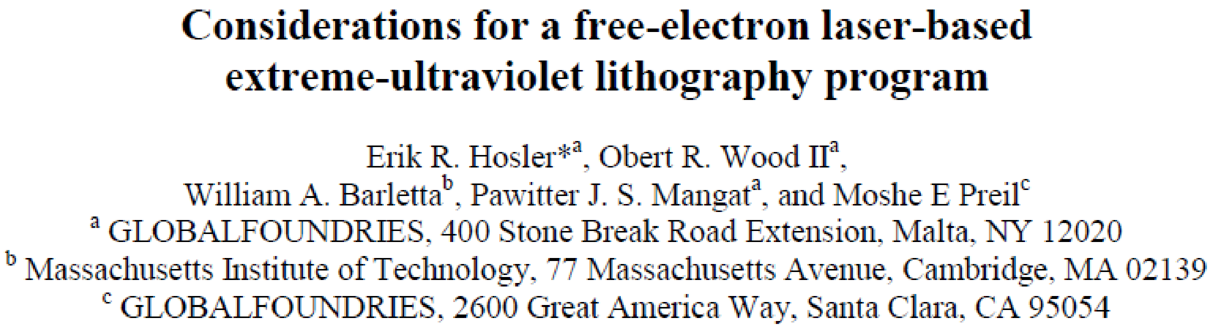
An EUV FEL for Lithography

- Joint paradigm shift
  - FEL not for the single user…
  - Lithography tool does not have a single source…

- Single purpose facility
  - Support entire EUV lithography sector
  - No need for adjustable wavelengths
  - Need high-average power
  - Minimal coherence, maximum divergence

- Pulse duration
  - No strict requirement for lithography…besides avoiding ablation
  - Necessarily short as a result of FEL efficiency
  - Long pulse duration EUV FEL emission will increase optics lifetime → limit peak power

- Scaling to 6.x nm?
  - Necessary changes in exposure equipment, mask blanks and mirror may represent an economic roadblock
  - EUV self-aligned techniques or multi-pattering



Considerations for a free-electron laser-based extreme-ultraviolet lithography program

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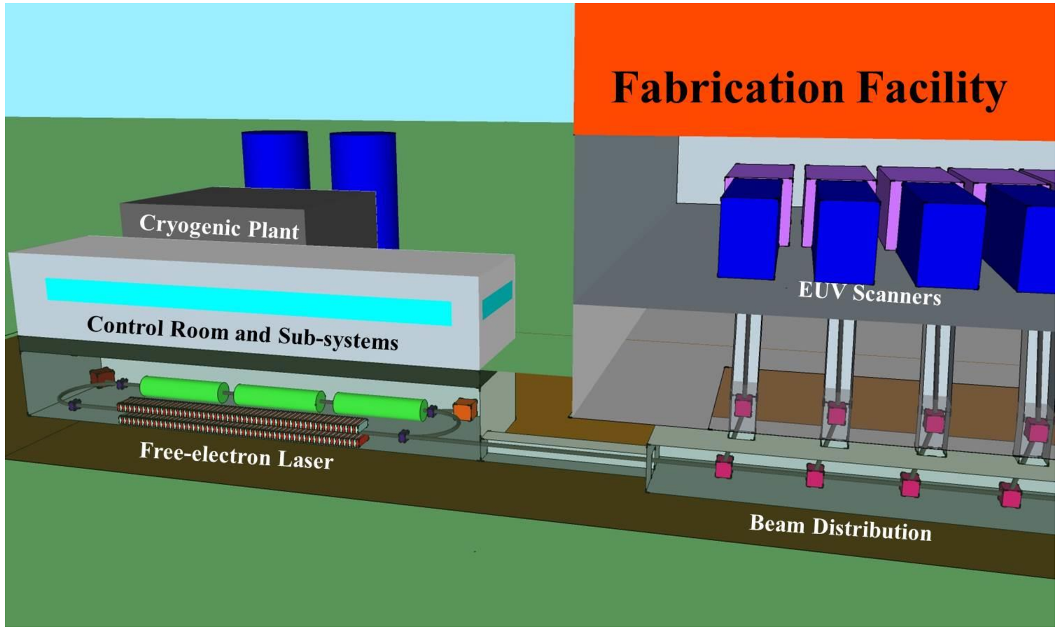
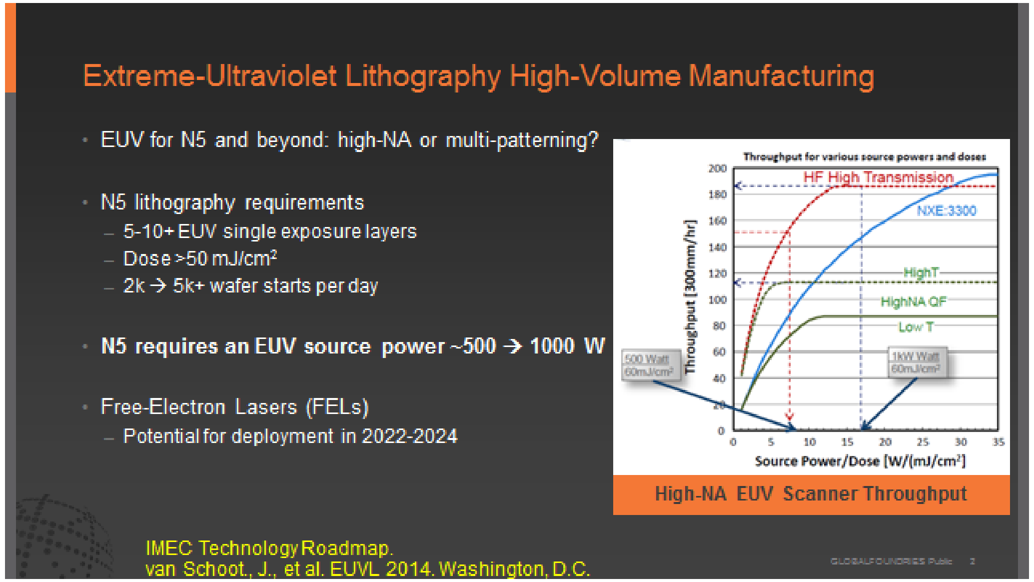


E.R. Hosler, O.R. Wood and M.E Preil. Extending extreme-UV lithography technology. SPIE Newsroom. 2016.

Need for a Scorecard…

- A free-electron laser-based EUV lithography program may be the most economical means for HVM operation
  - Line edge/width roughness and CD requirements for future technology nodes may require high-dose resists
- Choice of free-electron laser emission architecture will impact HVM lithography operations
  - Stability of accelerator, undulator, and other sub-systems will affect overall machine performance
- **FEL-Lithography scorecard is outlined**
  - **SIMPLEX is utilized to explore the FEL emission architecture parameter space**



Extreme-Ultraviolet Lithography High-Volume Manufacturing

- EUV for N5 and beyond: high-NA or multi-patterning?
- N5 lithography requirements
  - 5-10+ EUV single exposure layers
  - Dose >50 mJ/cm²
  - 2k → 5k+ wafer starts per day
- **N5 requires an EUV source power ~500 → 1000 W**
- Free-Electron Lasers (FELs)
  - Potential for deployment in 2022-2024

High-NA EUV Scanner Throughput

IMEC Technology Roadmap.
van Schoot, J., et al. EUVL 2014. Washington, D.C.

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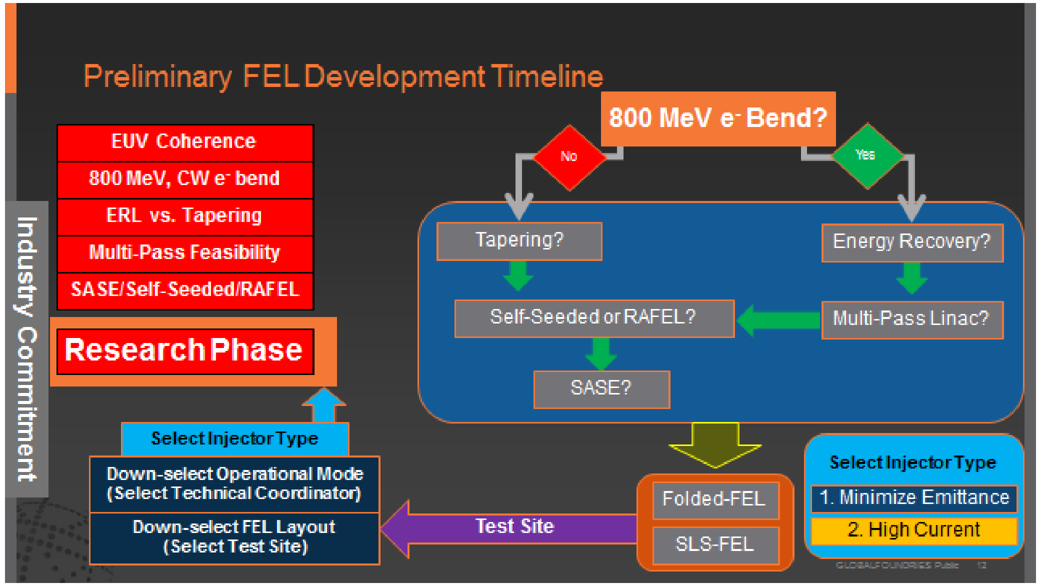

Preliminary FEL Development Timeline

Industry Commitment

EUV Coherence
800 MeV, CW e⁻ bend
ERL vs. Tapering
Multi-Pass Feasibility
SASE/Self-Seeded/RAFEL

Research Phase

Select Injector Type
Down-select Operational Mode (Select Technical Coordinator)
Down-select FEL Layout (Select Test Site)

800 MeV e⁻ Bend?

No
Tapering?
Self-Seeded or RAFEL?
SASE?

Yes
Energy Recovery?
Multi-Pass Linac?

Folded-FEL
SLS-FEL

Test Site

Select Injector Type
1. Minimize Emittance
2. High Current

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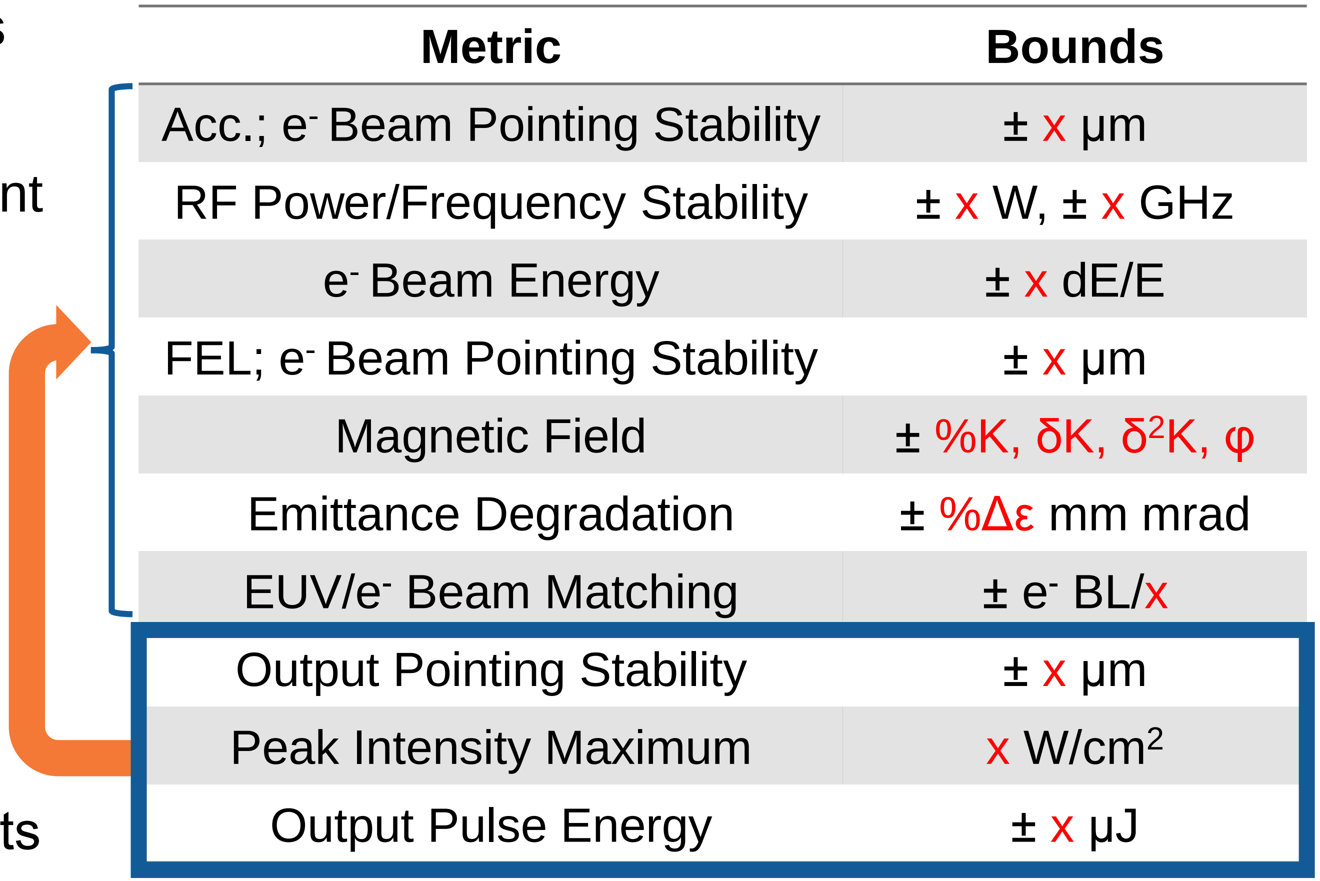
Development of a Lithography-based FEL Scorecard

- Evolving evaluation of various FEL options
- FEL emission architecture will drive different bounds
  - SASE: self-amplified spontaneous emission
  - SS: self-seeding
  - RAFEL: regenerative amplifier FEL
- FEL requirements will drive machine specifications
- Lithographers ↔ Accelerator/FEL Physicists
  - Scorecard needs to be re-evaluated for each accelerator and FEL configuration



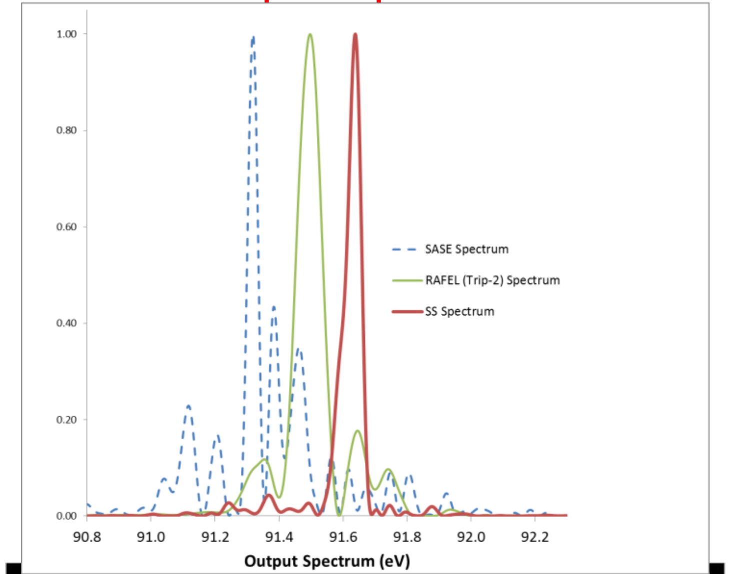
Metric	Bounds
Acc.; e^- Beam Pointing Stability	± x µm
RF Power/Frequency Stability	± x W, ± x GHz
e^- Beam Energy	± x dE/E
FEL; e^- Beam Pointing Stability	± x µm
Magnetic Field	± %K, δK, δ^2K, φ
Emittance Degradation	± %Δε mm mrad
EUV/e^- Beam Matching	± e^- BL/x
Output Pointing Stability	± x µm
Peak Intensity Maximum	x W/cm^2
Output Pulse Energy	± x µJ

E.R. Hosler, O.R. Wood and M.E Preil. International EUVL Symposium. Maastrict, Netherlands. 2015.

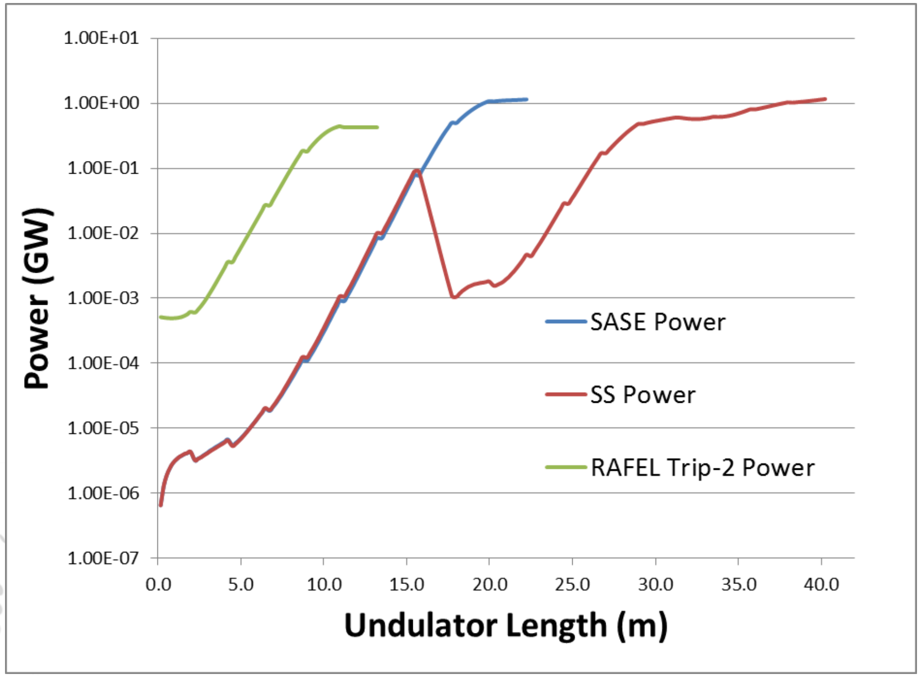
FEL Emission Architecture – Base Configuration Comparison

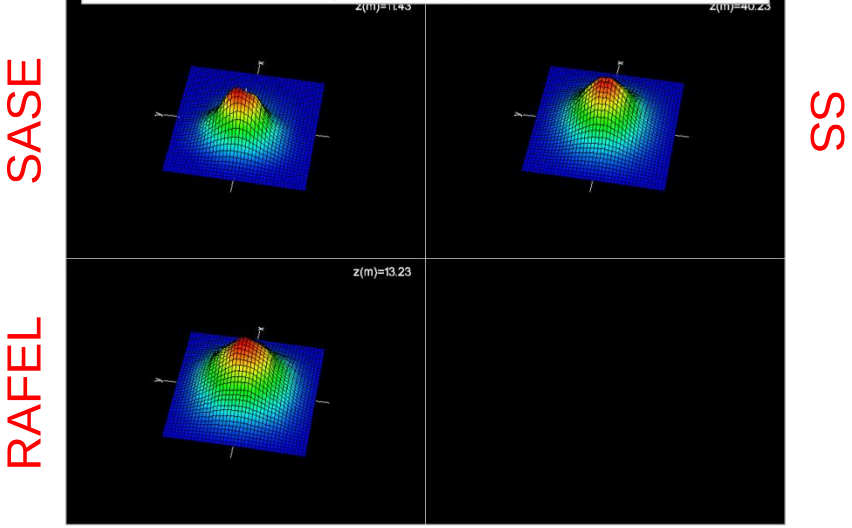
- SASE has the most rapid build-up
- SS gives the most narrow output spectrum
  - All outputs are well within the standard EUV Mo/Si multi-layer mirror bandwidth
- Photon flux spatial distribution is similar for all cases

Output Spectrum



Power Build-up Comparison





Evaluation of planned Lithography-based FEL Scorecard

- Baseline FEL emission architecture were defined and are currently being explored in detail
  - **SASE**
    - Evaluated for several parameters, **more robust to fluctuations, higher variation in photon energy**
  - **SS**
    - Improve monochromator design, evaluate similar parameters as with SASE
    - **More sensitive to fluctuations**
    - **More critical parameters**
  - **RAFEL**
    - Investigate feedback physics: explanation for not attaining steady-state power output

- As evaluation progresses, launch discussions with equipment suppliers and existing light source operators

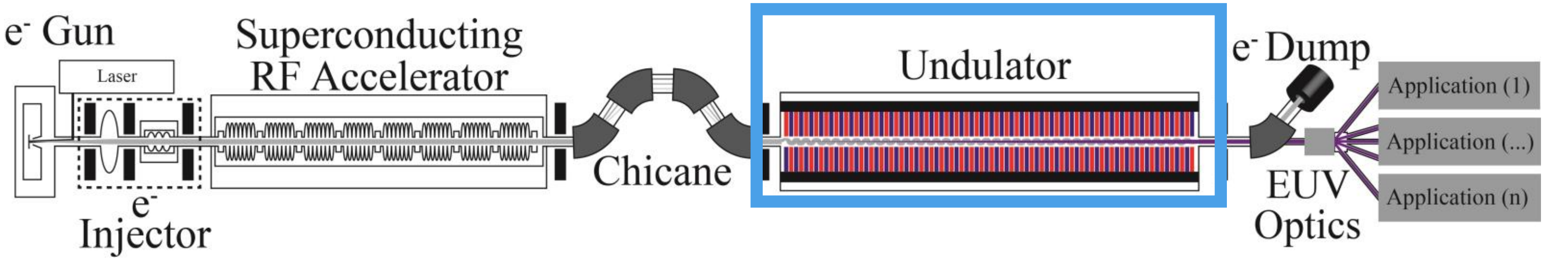
- **Lithographers ↔ Accelerator/FEL Physicists**

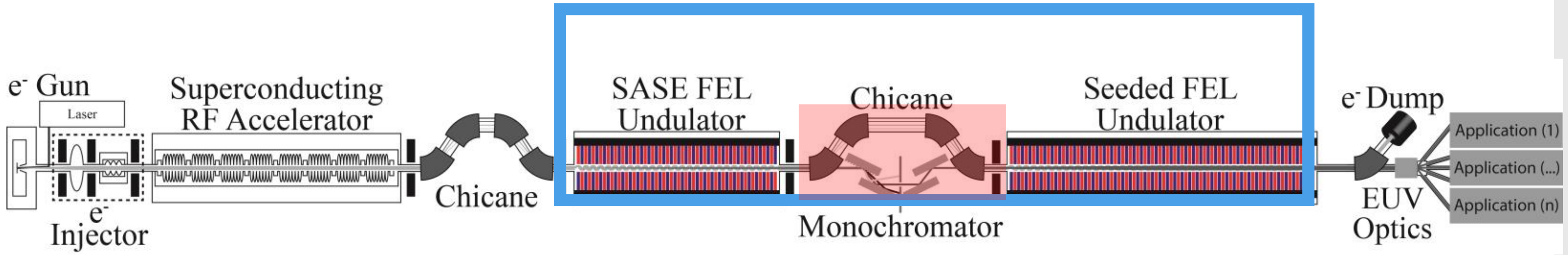
Metric	**Bounds**
Acc.; e^- Beam Pointing Stability	± x μm
RF Power/Frequency Stability	± x W, ± x GHz
e^- Beam Energy	± **0.25%** dE/E
FEL; e^- Beam Pointing Stability	± x μm
Magnetic Field	± **2E-4%**, δK, δ^2K, φ
e^- Bunch Emittance	**ε < 0.3** mm mrad
EUV/e^- Beam Matching	± **e^- BL/3**
Output Pointing Stability	± x μm
Peak Intensity Maximum	x W/cm^2
Output Pulse Energy	± x μJ

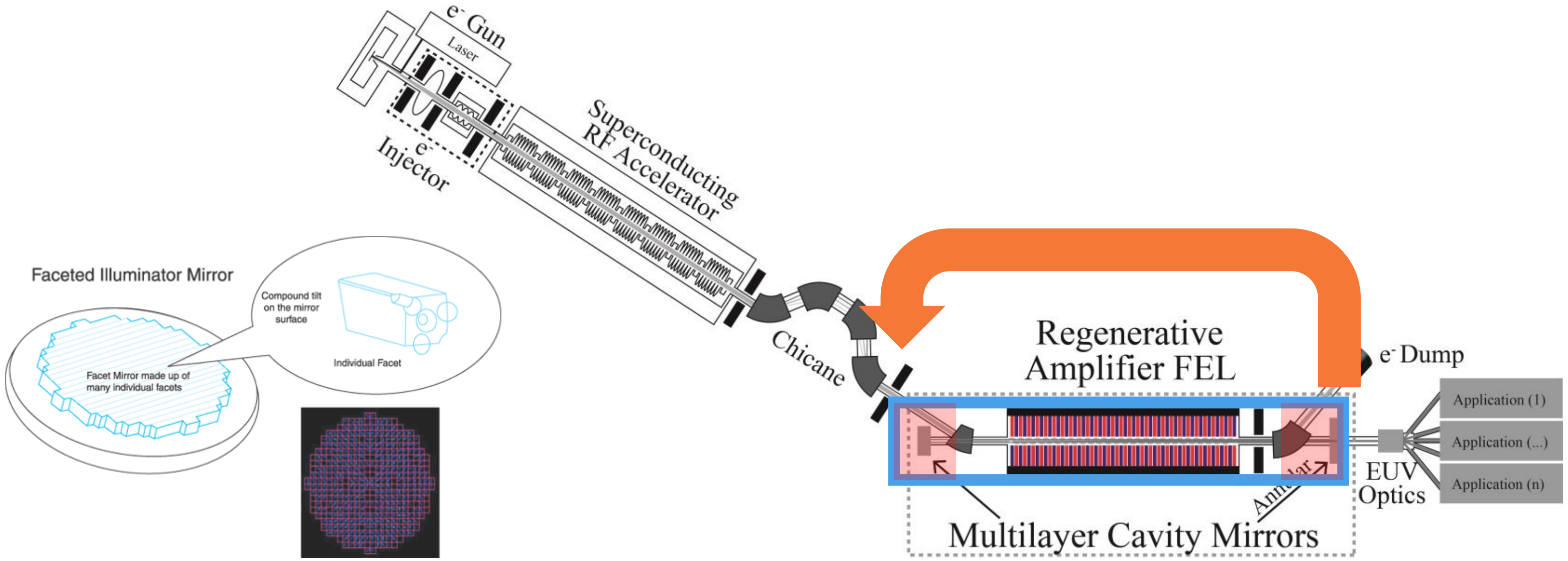
E.R. Hosler, O.R. Wood and M.E Preil. International EUVL Symposium. Maastrict, Netherlands. 2015.

Configuration Pitfalls

- SASE
  - Wavelength instability
  - Power instability
- Self-seeding
  - Amplification instability
  - Power instability
- RAFEL
  - Untested in the EUV
  - Optics survivability
- All modes
  - Coherence breaking
  - RF instabilities

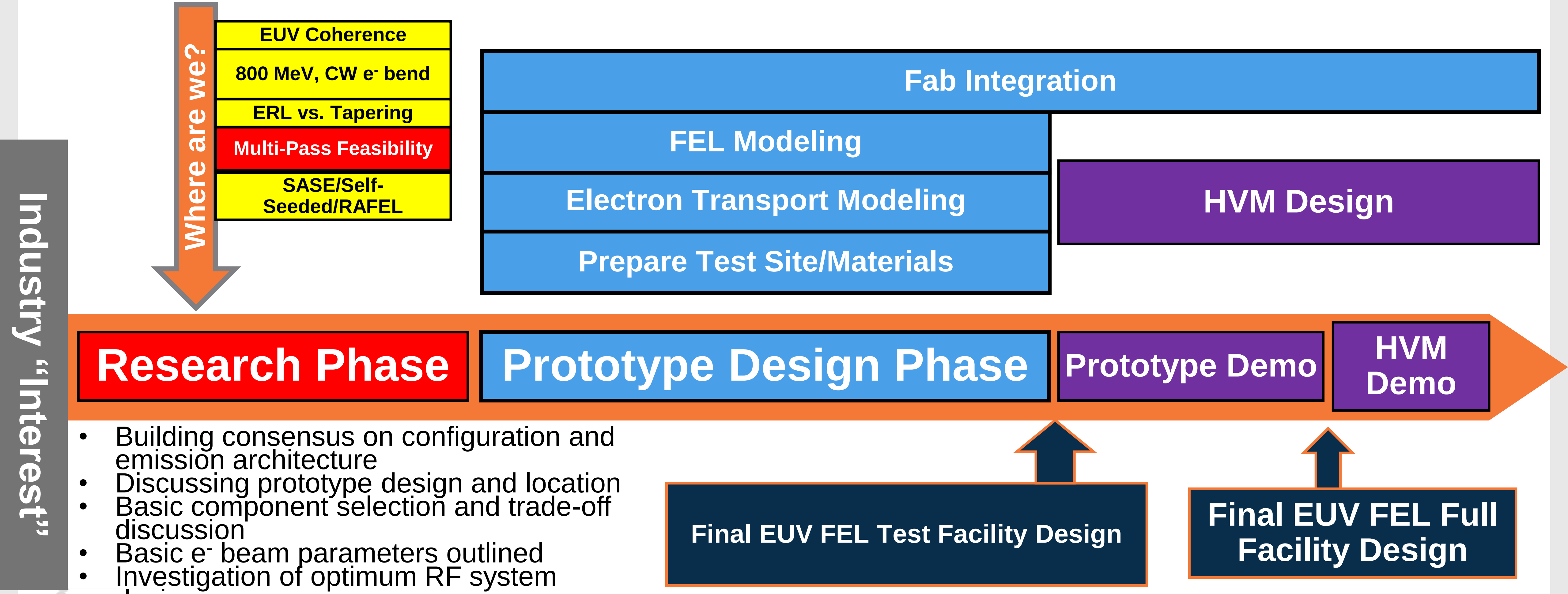






N. Harned, S. Roux, P. Ware, and A. Tanimoto. Progress Report: Engineers take the EUV lithography challenge. OEMagazine. DOI: 10.1117/2.5200302.0003. 2003.

FEL Development Timeline Progress



Industry “Interest”

Where are we?

EUV Coherence

800 MeV, CW e^- bend

ERL vs. Tapering

Multi-Pass Feasibility

SASE/Self-Seeded/RAFEL

Fab Integration

FEL Modeling

Electron Transport Modeling

Prepare Test Site/Materials

HVM Design

Research Phase

Prototype Design Phase

Prototype Demo

HVM Demo

- Building consensus on configuration and emission architecture
- Discussing prototype design and location
- Basic component selection and trade-off discussion
- Basic e^- beam parameters outlined
- Investigation of optimum RF system design
- Coherence mitigation schemes proposed

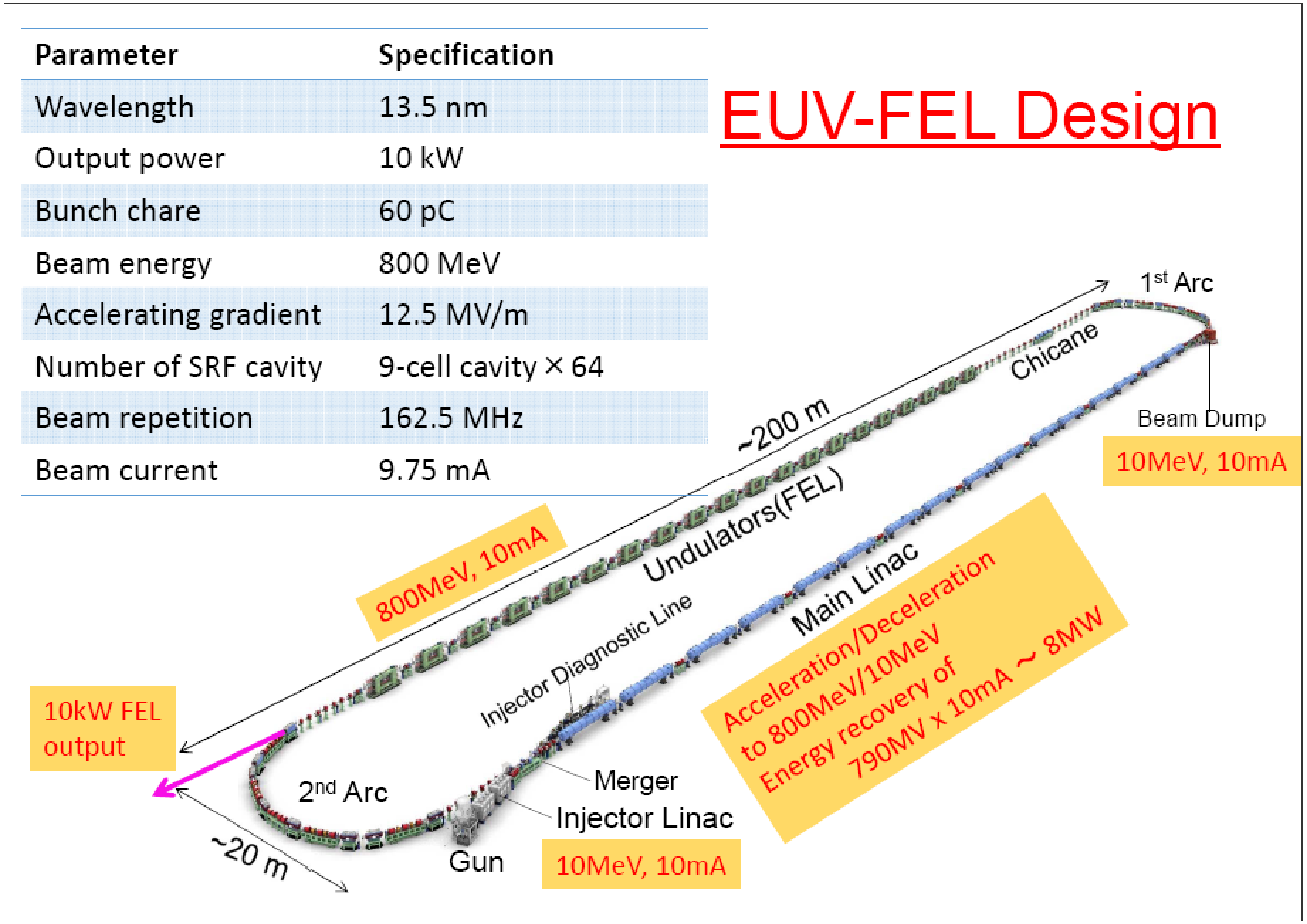
Final EUV FEL Test Facility Design

Final EUV FEL Full Facility Design

Keens, S.G., Rossa, B., Frei, M., Free-electron lasers for 13nm EUV lithography: RF design strategies to minimise investment and operational costs. Proceedings of SPIE 9776, Extreme Ultraviolet (EUV) Lithography VI. 97760T. 2016.
Pina, L. EUV Source Workshop. 2014.

KEK cERL for EUV-FEL

- Use of existing technology
  - Expertise in ERL
  - Superconducting Test Facility @ KEK
- Existing experimental hall
- Target 10 mA operation
- Phase space modeling of 800 MeV e$^-$ beam recirculation
- Predict ~20 kW @ 10 mA with 8% tapering
- **Update by Ryukou Kato (P43)**



EUV-FEL Design

Parameter	Specification
Wavelength	13.5 nm
Output power	10 kW
Bunch chare	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m
Number of SRF cavity	9-cell cavity × 64
Beam repetition	162.5 MHz
Beam current	9.75 mA

Umemori, K. EUV Source Workshop. 2015.

Driving toward an industrial EUV FEL

- Success is two fold dependent
  - Development of new technology
  - Acceptance
- FEL/Accelerator Paradigm Shift
  - Power and availability are king
  - Single to many end stations
- Any development program must have a governance body
  - Semiconductor manufacturers
  - EUV Scanner Supplier(s)
  - Accelerator/FEL Research Team

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Thank you!

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