EUV free-electron laser requirements and considerations for semiconductor manufacturing

Erik R. Hosler[1], Obert R. Wood II[1] and William A. Barletta[2]

[1]GLOBALFOUNDRIES

[2]Massachusetts Institute of Technology

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1. Current EUV Lithography Status
2. Why do we need FELs?
3. Lithographer’s Perspective on FELs
4. FEL Research Developments
5. GLOBALFOUNDRIES FEL Research

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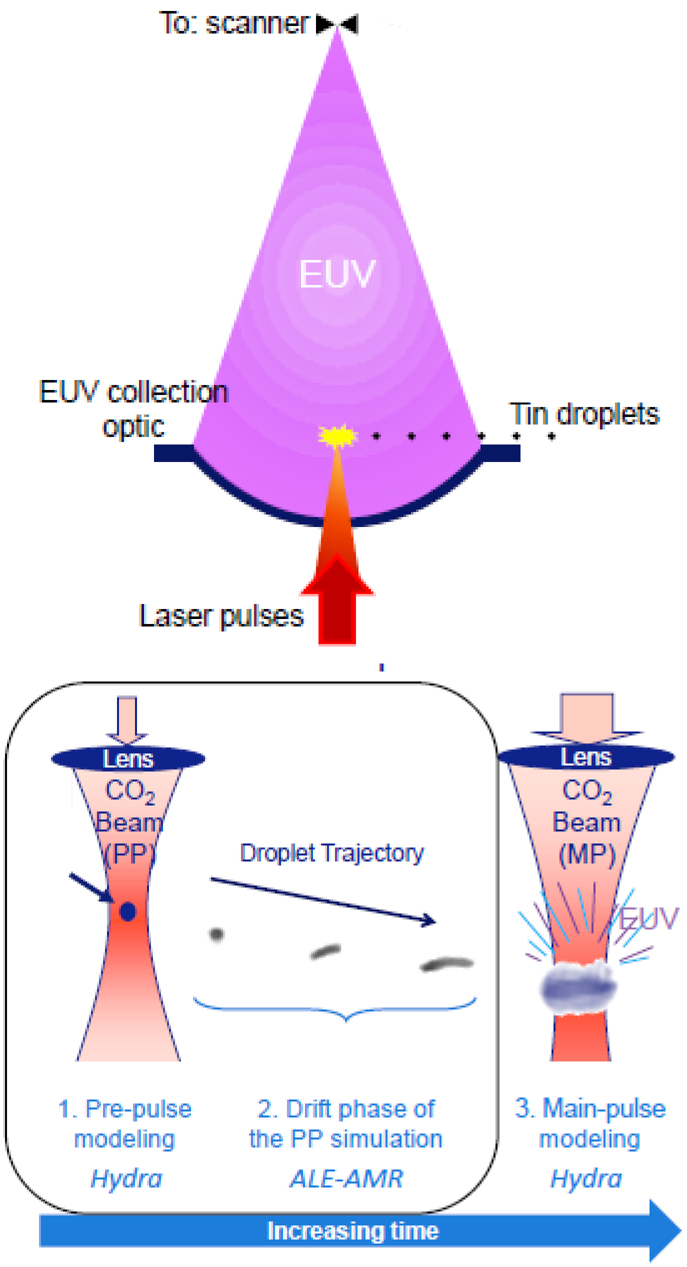
EUV Source for HVM – State of the Art

- Laser-produced plasma (LPP) source
  - High-power CO_2 laser
  - Sn droplet source
  - Complex feedback and control systems

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

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

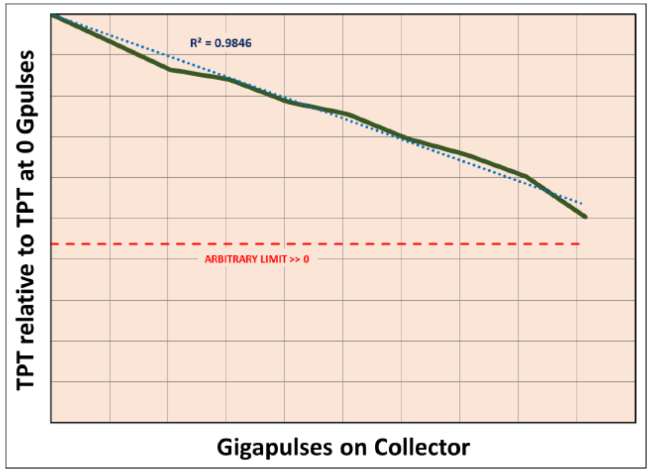


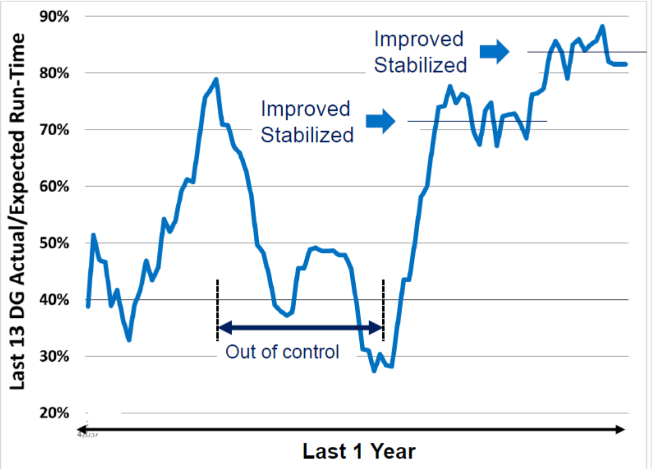
Pirati, A., et al. SPIE Proc. EUVL, 2016.
Purvis, M., et al. SPIE Proc. EUVL, 2016.

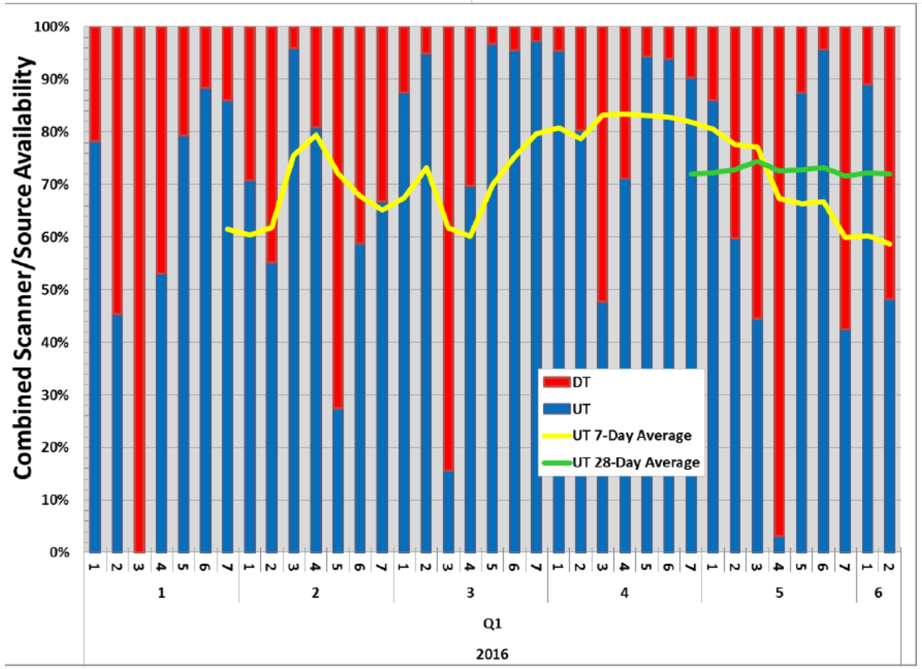
Laser-produced plasma source challenges in HVM

- Availability and consistent performance
  - Tin
    - Collector
    - Droplet Generator
  - Laser
  - Control Systems

- **Progress and Confidence**
- “Introduction is gated by the number of technology development wafers that can be consistently processed…” -Intel

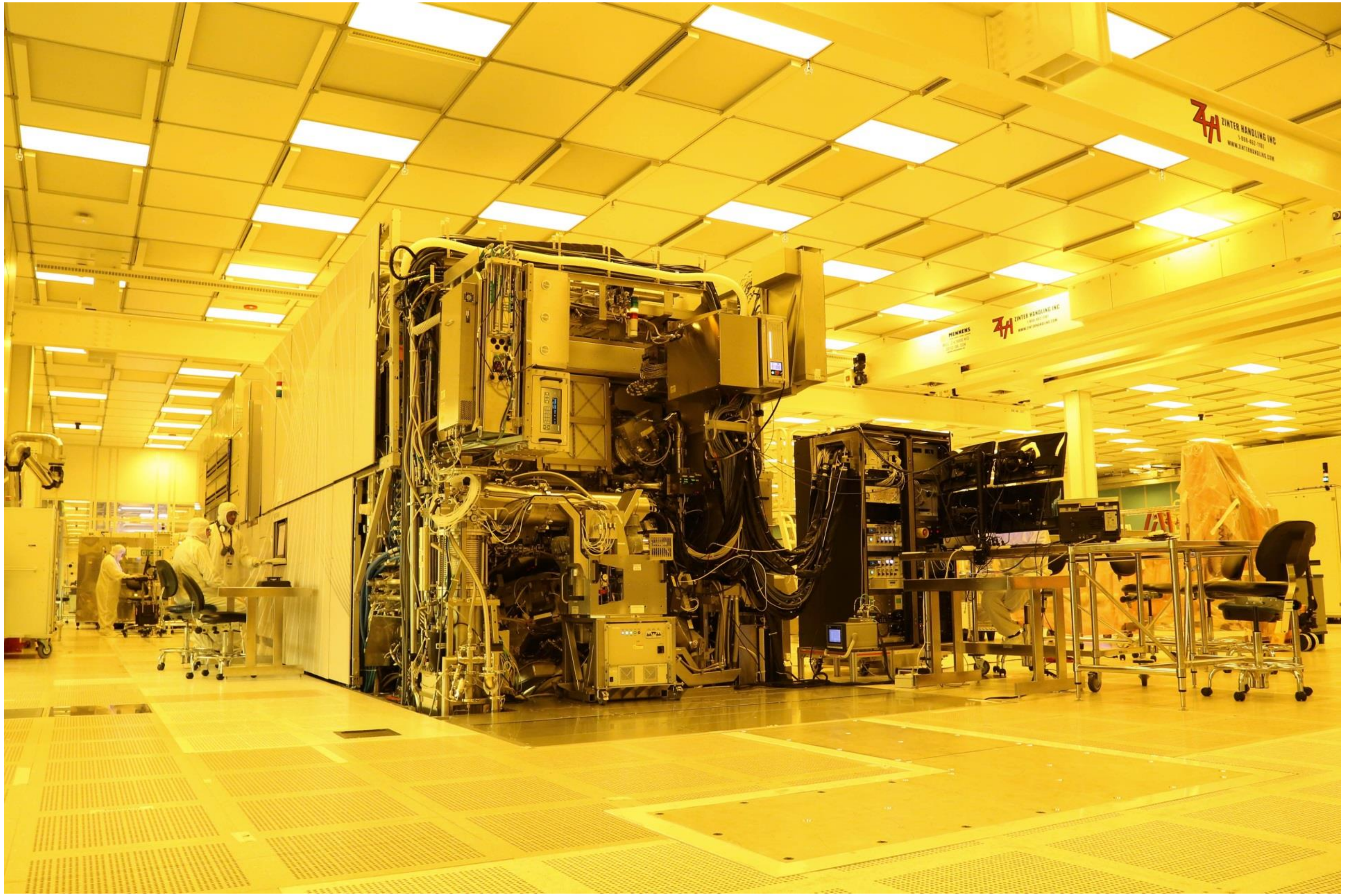






Britt Turkot. SPIE: Advanced Lithography, EUVL. 2016.

Albany EUV Scanner



Dan Corliss, IBM Research Alliance. 2016.

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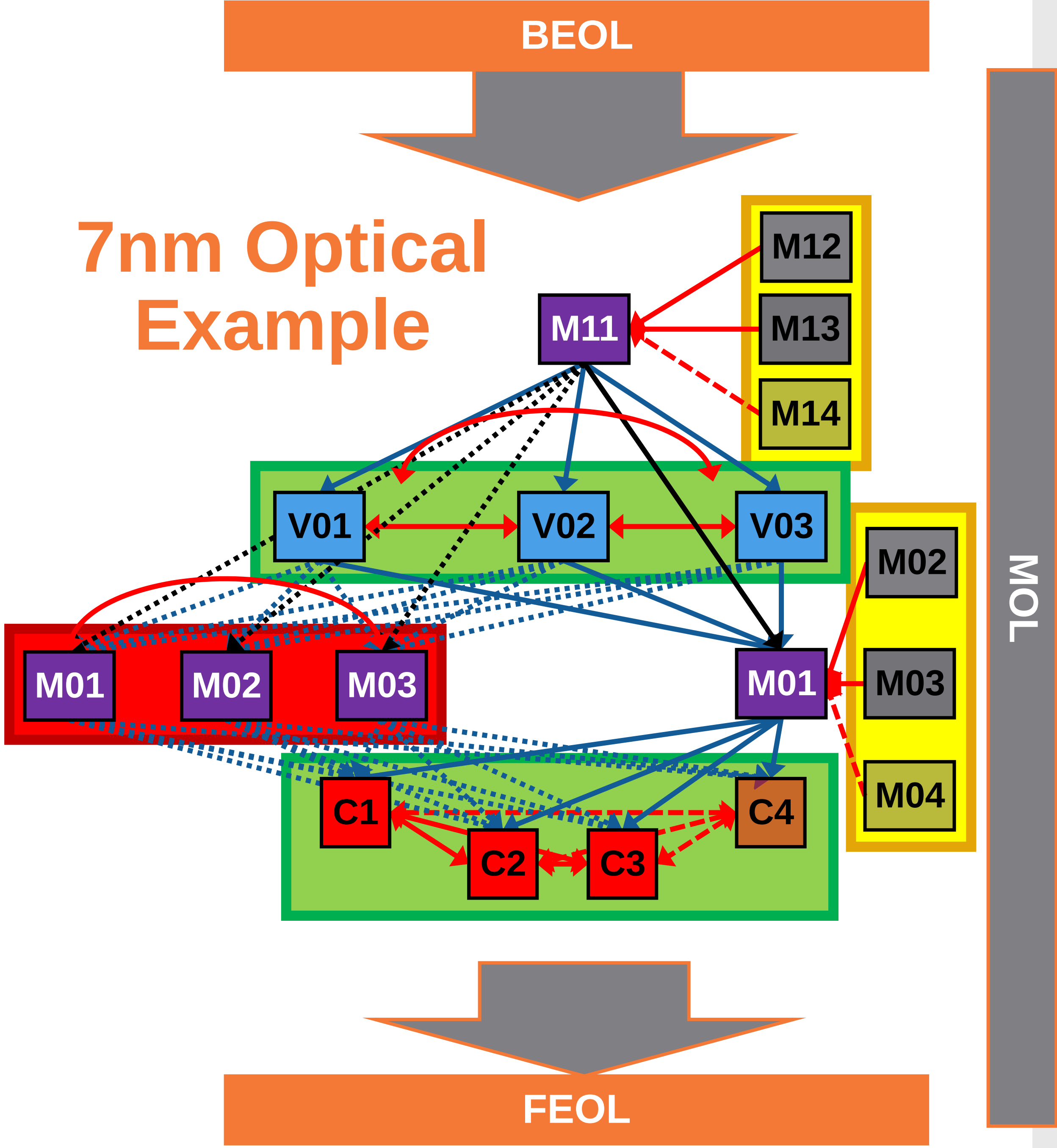
Why EUV?

Cost Effectiveness

- EUV insertion…7nm? 5nm? Beyond?
  - LELE → LELELE → SADP/SAQP
- Productivity is key
- Need lithography performance at dose



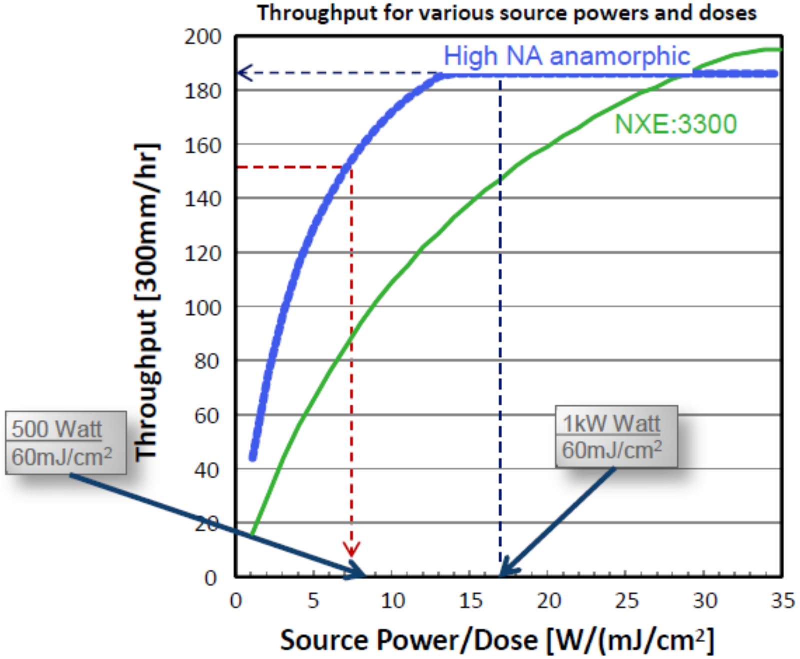
Extreme-Ultraviolet Lithography High-Volume Manufacturing

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

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

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

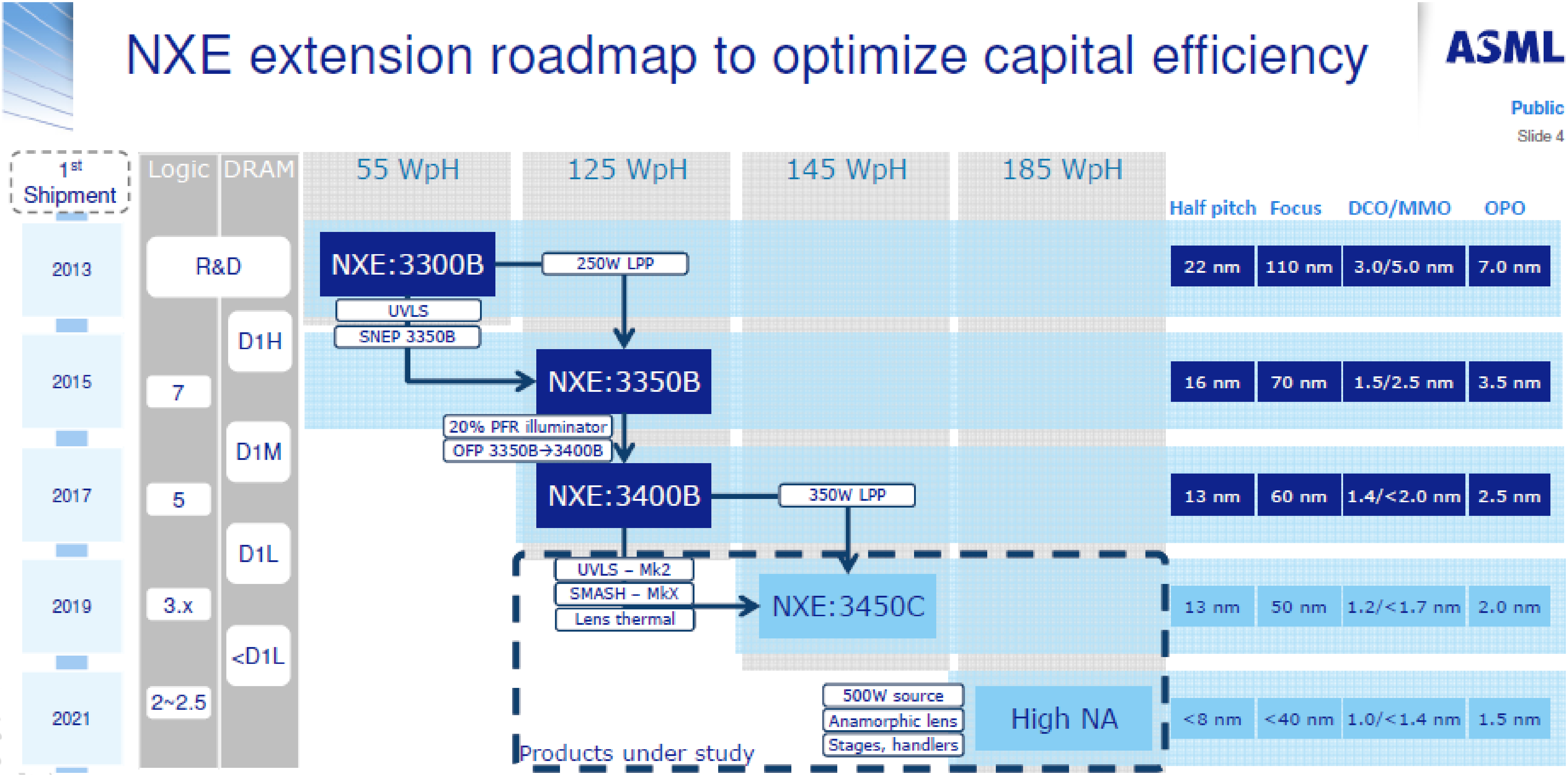
- Free-Electron Lasers (FELs)
  - Potential for deployment by ***2024***



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.

ASML EUV Roadmap



NXE extension roadmap to optimize capital efficiency

ASML

Public

Slide 4

1st Shipment	Logic	DRAM	Product	Throughput	Half pitch	Focus	DCO/MMO	OPO
2013	R&D		NXE:3300B	55 WpH	22 nm	110 nm	3.0/5.0 nm	7.0 nm
2015	7	D1H	NXE:3350B	125 WpH	16 nm	70 nm	1.5/2.5 nm	3.5 nm
2017	5	D1M	NXE:3400B	125 WpH	13 nm	60 nm	1.4/<2.0 nm	2.5 nm
2019	3.x	D1L	NXE:3450C	145 WpH	13 nm	50 nm	1.2/<1.7 nm	2.0 nm
2021	2~2.5	<D1L	High NA	185 WpH	<8 nm	<40 nm	1.0/<1.4 nm	1.5 nm

NXE:3300B → 250W LPP; UVLS; SNEP 3350B → NXE:3350B

NXE:3350B → 20% PFR illuminator; OFP 3350B→3400B → NXE:3400B

NXE:3400B → 350W LPP; UVLS – Mk2; SMASH – MkX; Lens thermal → NXE:3450C

500W source; Anamorphic lens; Stages, handlers → High NA

Products under study

Pirati, A., et al. SPIE Proc. EUVL, 2016.

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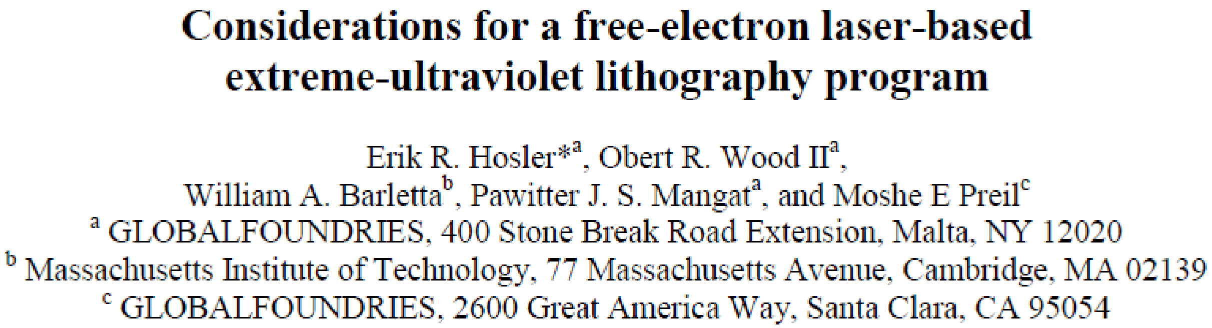
Lithographic Requirements

- An EUV FEL must power multiple scanners simultaneously
- **FEL EUV source must operate with an availability of 100%**
  - Redundancy of high-risk/low-cost machine components
  - Minimizing stress on long replacement time components
  - **Two FELs must be run simultaneously!**
- **Cost**
  - FEL EUV program must be substantially cheaper (depreciation + OpEx) and more powerful than an equivalent number of LPP sources to justify development risk
  - How many EUVL sources are required for HVM?
    - 7 nm Logic roadmap from IMEC says 5-10 EUV layers
    - 3-4 L/S (>25 mJ/cm^2), 2-6 contact (>35 mJ/cm^2) = 10x 250 W LPP tools for ~50k wafers/month
- Other: FEL Specific
  - Beam Distribution
    - High power, splitting efficiency
  - Power management and Facility Size
    - On mask, on mirrors, on wafer, into beam dump, and electrical power
    - Integrate with existing fab architecture
  - Coherence
    - Manipulate at scanner or within distribution system?
  - Harmonic mitigation scheme
    - FELs produce a few percent of the fundamental power in higher harmonics
  - Wavelength stability? Optical bandwidth? Power stability (Dose repro <0.2%)?

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

Erik R. Hosler*[a], Obert R. Wood II[a],
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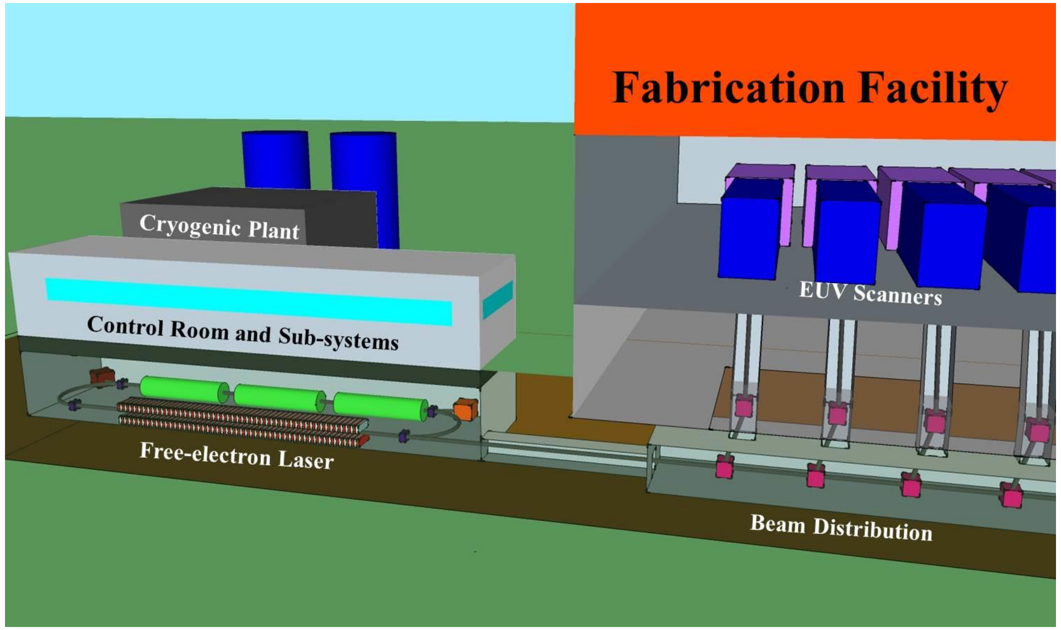
[b] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
[c] GLOBALFOUNDRIES, 2600 Great America Way, Santa Clara, CA 95054



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

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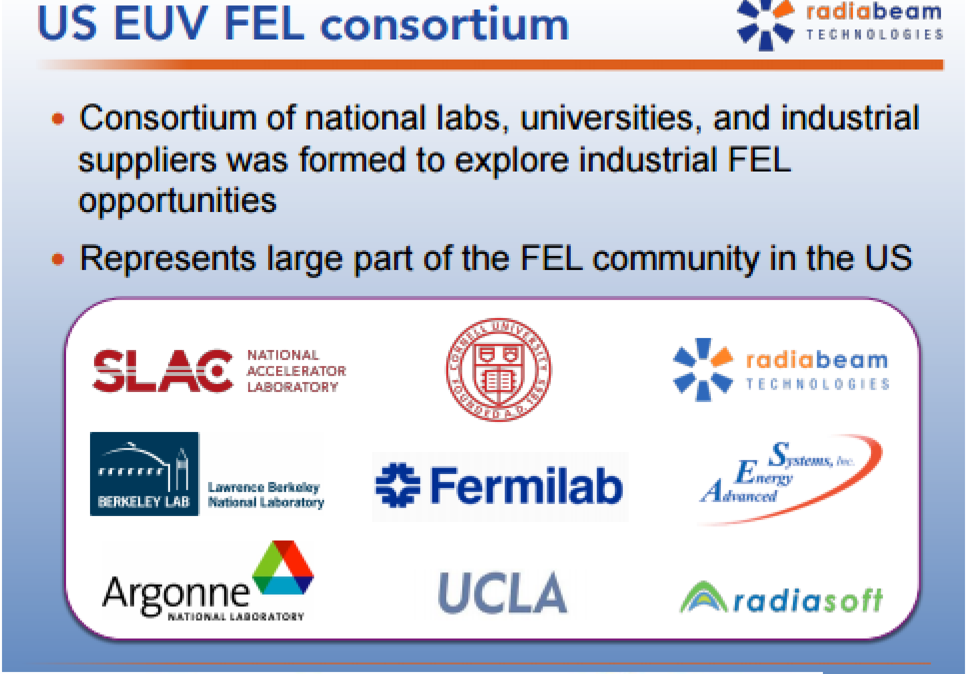
4	**FEL Research Developments**
5	GLOBALFOUNDRIES FEL Research

Stanford-Berkeley-FermiLab-RadiaBeam

- Leverage US expertise:
  - X-ray FEL (LCLS)
  - Particle colliders (FERMI)
  - Energy Recovery Systems (Cornell)
  - High-brightness e$^-$ gun (Berkeley, Cornell)
  - Industrialization and integration
- Minimize variables and risk for fast development
- ‘Off the shelf’ components



US EUV FEL consortium

radiabeam TECHNOLOGIES

- Consortium of national labs, universities, and industrial suppliers was formed to explore industrial FEL opportunities
- Represents large part of the FEL community in the US

SLAC NATIONAL ACCELERATOR LABORATORY

CORNELL UNIVERSITY FOUNDED A.D. 1865

radiabeam TECHNOLOGIES

BERKELEY LAB Lawrence Berkeley National Laboratory

Fermilab

Advanced Energy Systems, Inc.

Argonne NATIONAL LABORATORY

UCLA

radiasoft

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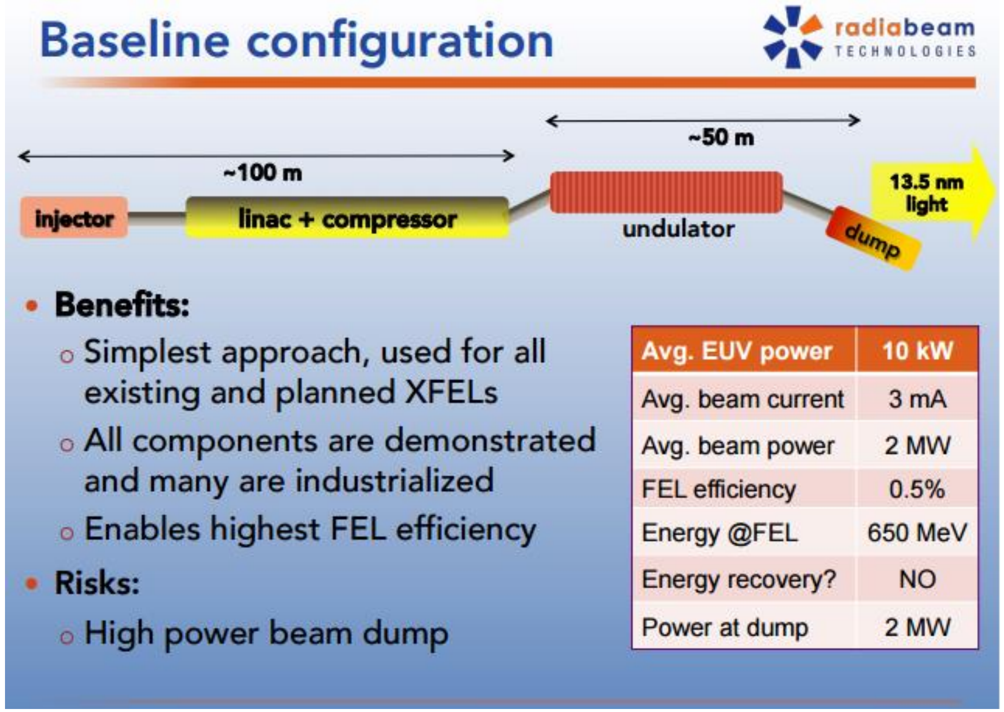


Baseline configuration

radiabeam TECHNOLOGIES

- **Benefits:**
  - Simplest approach, used for all existing and planned XFELs
  - All components are demonstrated and many are industrialized
  - Enables highest FEL efficiency
- **Risks:**
  - High power beam dump

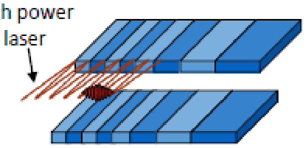
Avg. EUV power	10 kW
Avg. beam current	3 mA
Avg. beam power	2 MW
FEL efficiency	0.5%
Energy @FEL	650 MeV
Energy recovery?	NO
Power at dump	2 MW

TESSA

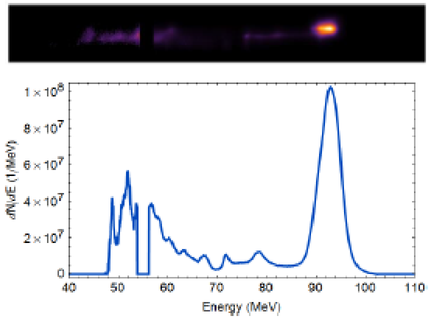
- How to drive higher efficiency?

Inverse FEL

- Broader view of undulator interaction: laser and e-beam, when at resonance inside the wiggler exchange energy)
- FEL is an amplifier and decelerator (laser absorbs energy from e-beam, albeit at a moderate rate < 1 MeV/m)
- IFEL is an accelerator: e-beam absorbs energy from the high power laser
- IFEL demonstrated energy exchange rate ~ 100 MeV/m, and design studies indicate possibility of 1 GeV/m
- ***Can we run IFEL in reverse?***

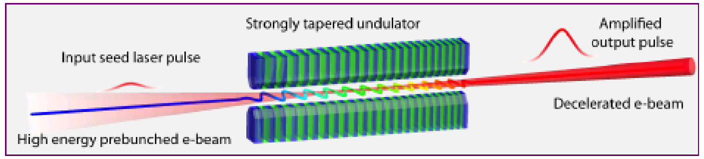


In an IFEL the electron beam absorbs energy from a radiation field.

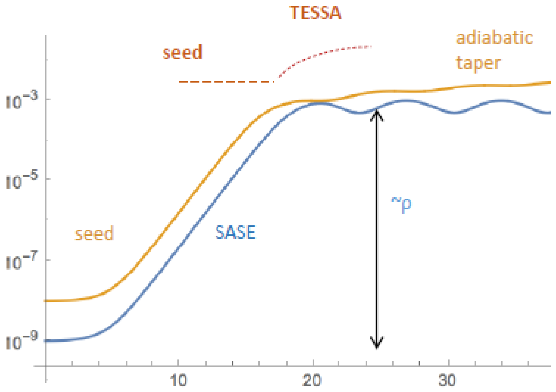


UCLA results from RUBICON experiments
J. Duris et al, *Nature Comm.* 5, 4928, 2014

TESSA

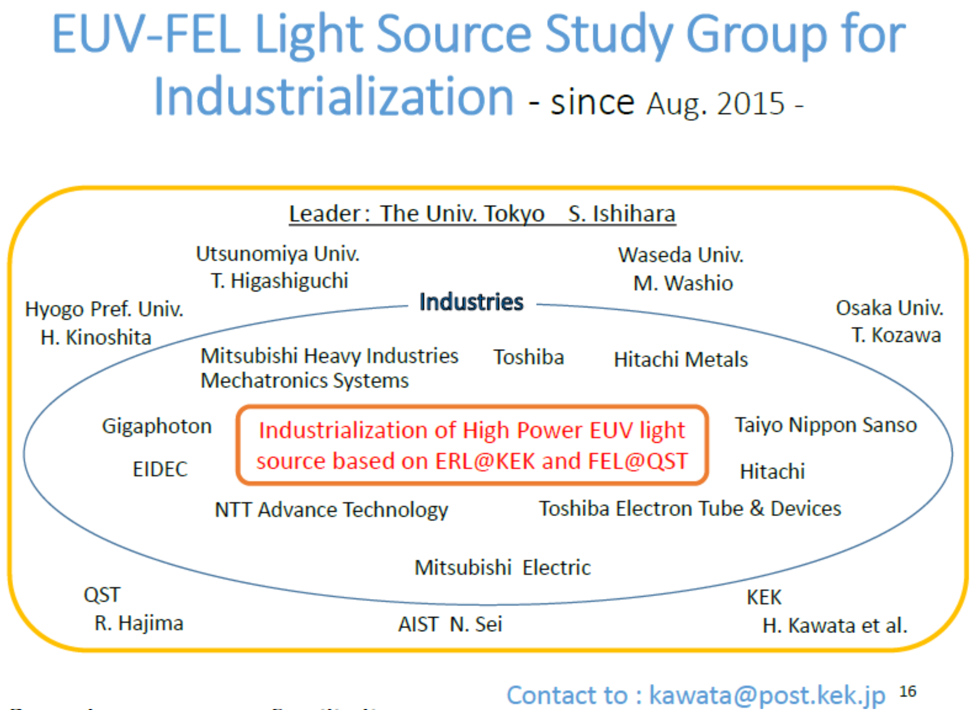


- Inverse IFEL = ~~FEL~~ TESSA (**T**apering **E**nhanced **S**timulated **S**uperradiant **A**mplification)
- E-beam rapid deceleration → laser amplification
- Requires seed pulse of high intensity (larger than P_{SAT})
- Tapering is optimized using proprietary GIT algorithm (Genesis Informed Tapering)



KEK

- Leverage Japan’s industrial infrastructure
  - Fully integrated development
- cERL
- Expand upon known techniques
- Drive to the highest reward design
- Initial study group meeting…today!



EUV-FEL Light Source Study Group for Industrialization - since Aug. 2015 -

Leader : The Univ. Tokyo S. Ishihara

Utsunomiya Univ.
T. Higashiguchi

Waseda Univ.
M. Washio

Hyogo Pref. Univ.
H. Kinoshita

Osaka Univ.
T. Kozawa

Industries

Mitsubishi Heavy Industries Mechatronics Systems

Toshiba

Hitachi Metals

Gigaphoton

EIDEC

Industrialization of High Power EUV light source based on ERL@KEK and FEL@QST

Taiyo Nippon Sanso

Hitachi

NTT Advance Technology

Toshiba Electron Tube & Devices

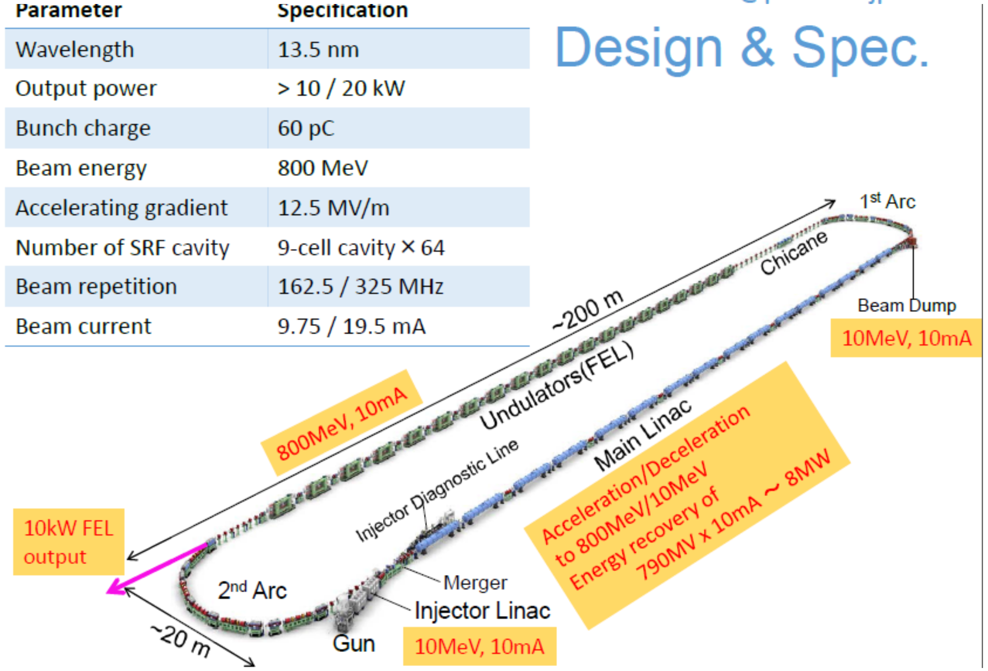
Mitsubishi Electric

QST
R. Hajima

AIST N. Sei

KEK
H. Kawata et al.

Contact to : kawata@post.kek.jp 16

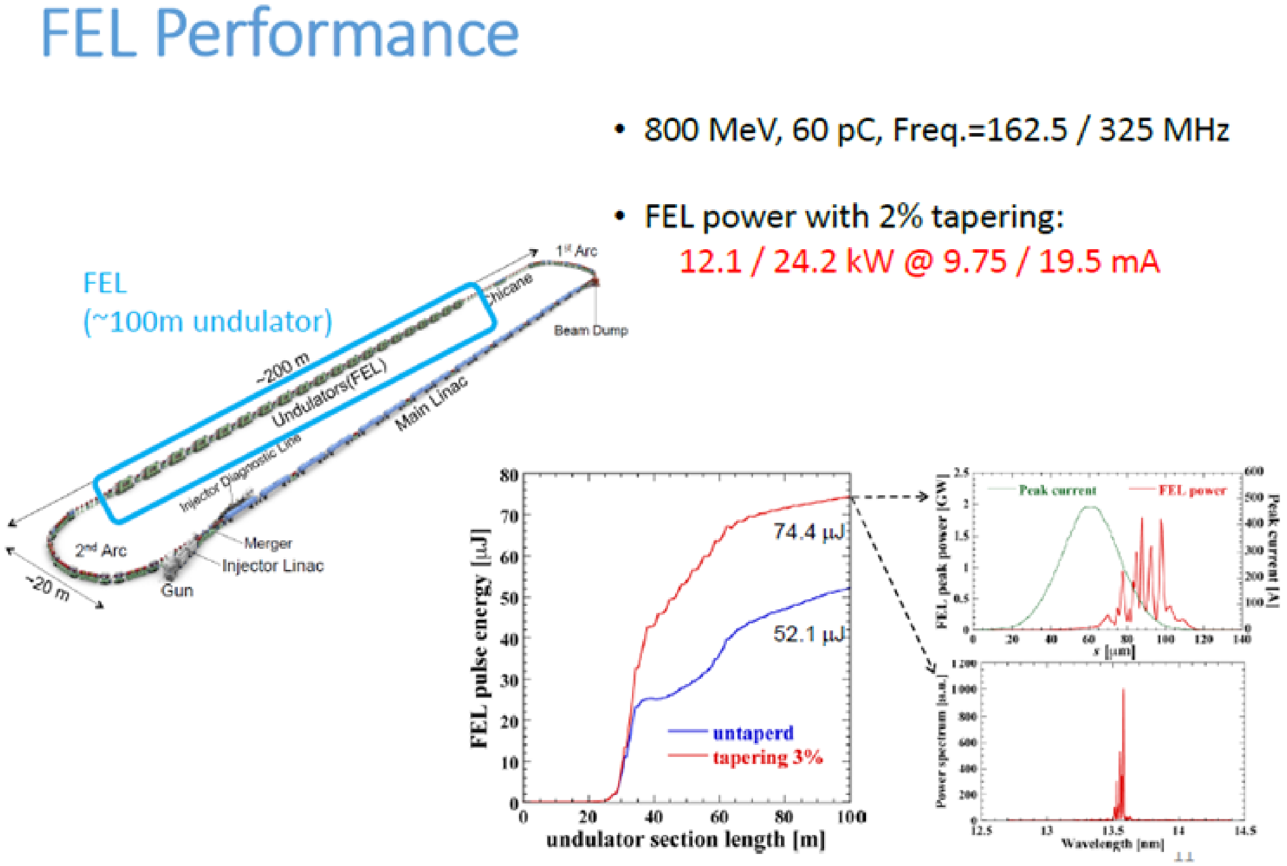


Design & Spec.

Parameter	Specification
Wavelength	13.5 nm
Output power	> 10 / 20 kW
Bunch charge	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m
Number of SRF cavity	9-cell cavity × 64
Beam repetition	162.5 / 325 MHz
Beam current	9.75 / 19.5 mA

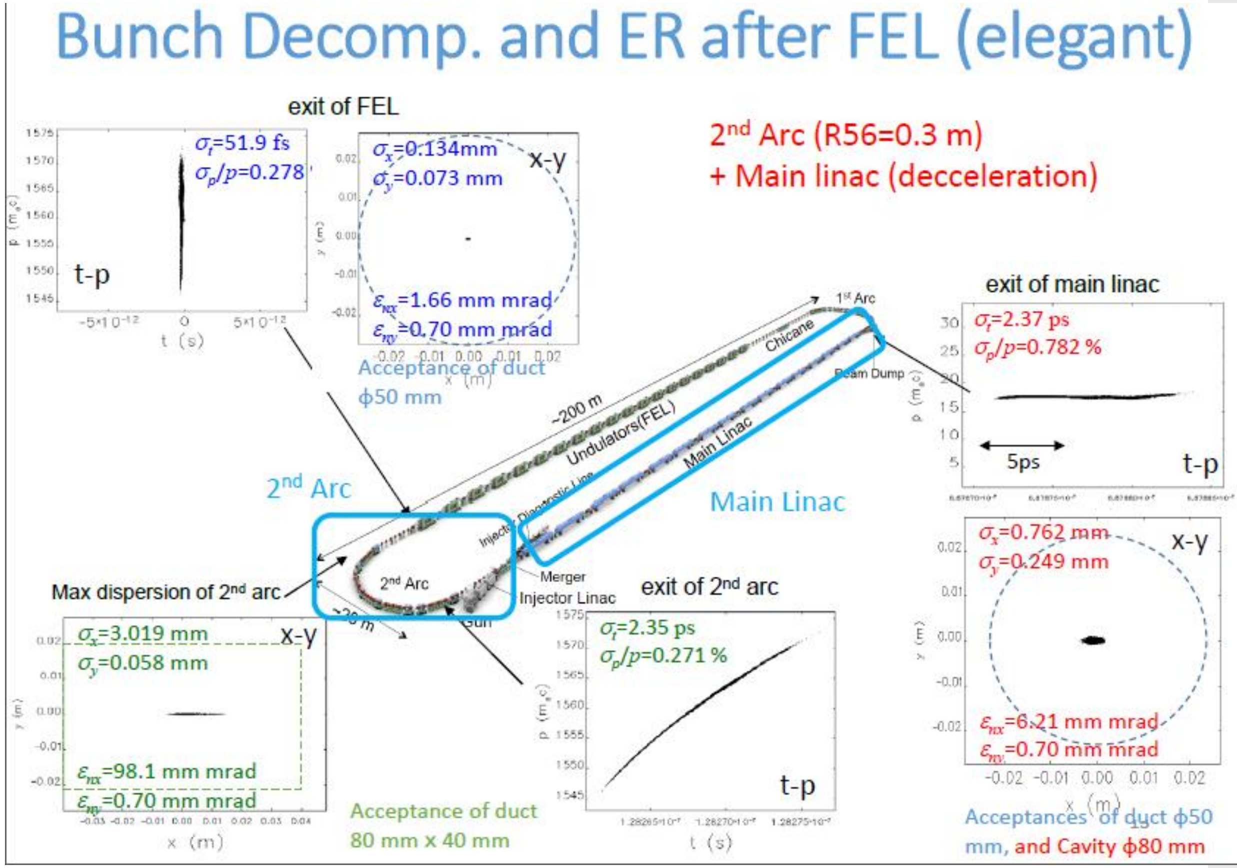
cERL

- Expand an existing toolset



FEL Performance

- 800 MeV, 60 pC, Freq.=162.5 / 325 MHz
- FEL power with 2% tapering:
  12.1 / 24.2 kW @ 9.75 / 19.5 mA

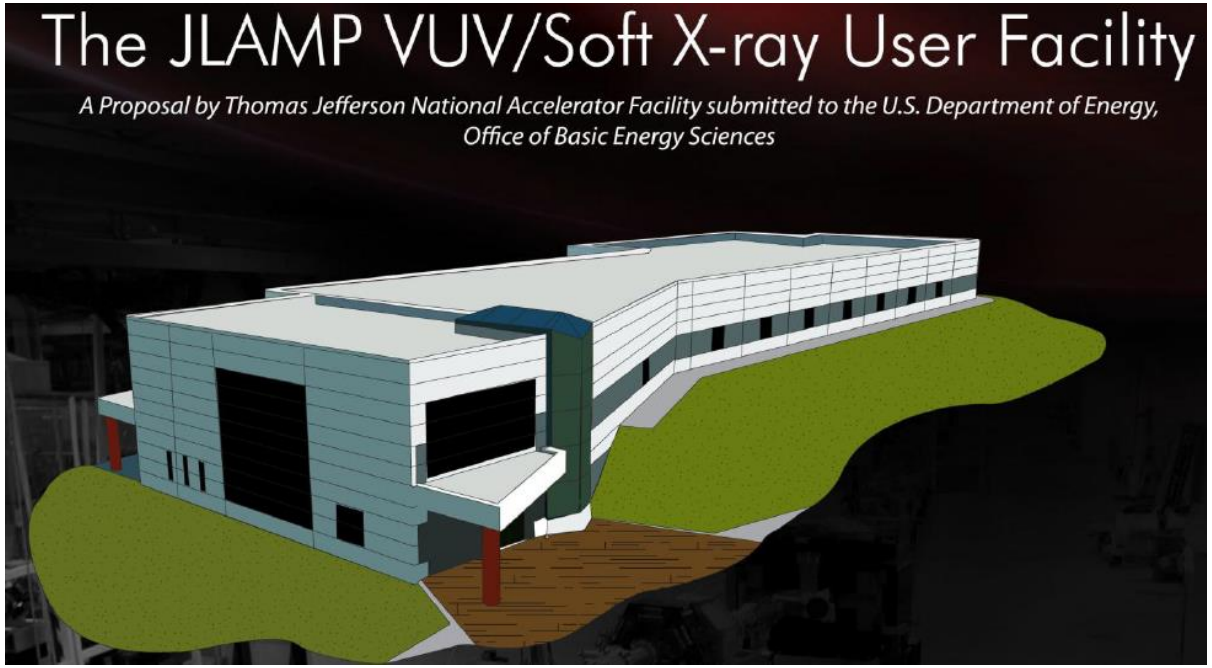


Bunch Decomp. and ER after FEL (elegant)

2nd Arc (R56=0.3 m)
+ Main linac (decceleration)

Jefferson Lab: JLAMP - An EUV FEL (2009 Proposal)

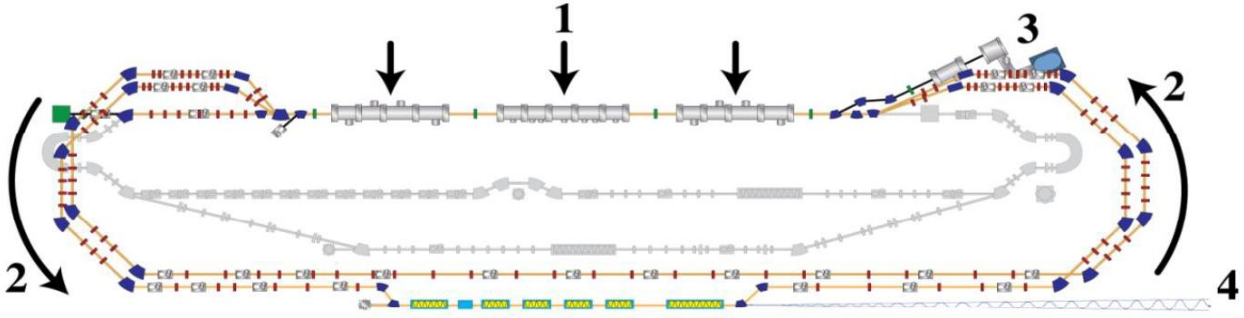
- Similar to c-ERL proposal
- Upgrades to existing facility:
  - Add advanced cryomodules (C100)
  - Add additional recirculation arc
  - Upgrade electron injector
  - Build EUV beamline and endstation
- ~$120M to execute at existing JLab facility



The JLAMP VUV/Soft X-ray User Facility

A Proposal by Thomas Jefferson National Accelerator Facility submitted to the U.S. Department of Energy, Office of Basic Energy Sciences

- Adaptable to EUV lithography light source
  - Must scale to 10’s kW output power
- After Proto?



Jefferson Lab: JLAMP Proposal. 2009.

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4 FEL Developments in the US

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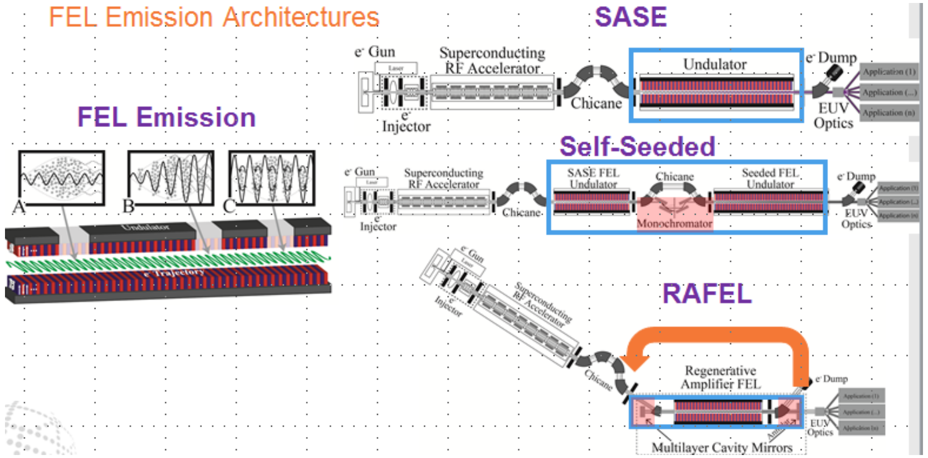
Evaluation of planned Lithography-based FEL Scorecard

- 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

SPIE Advanced Lithography 2017



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

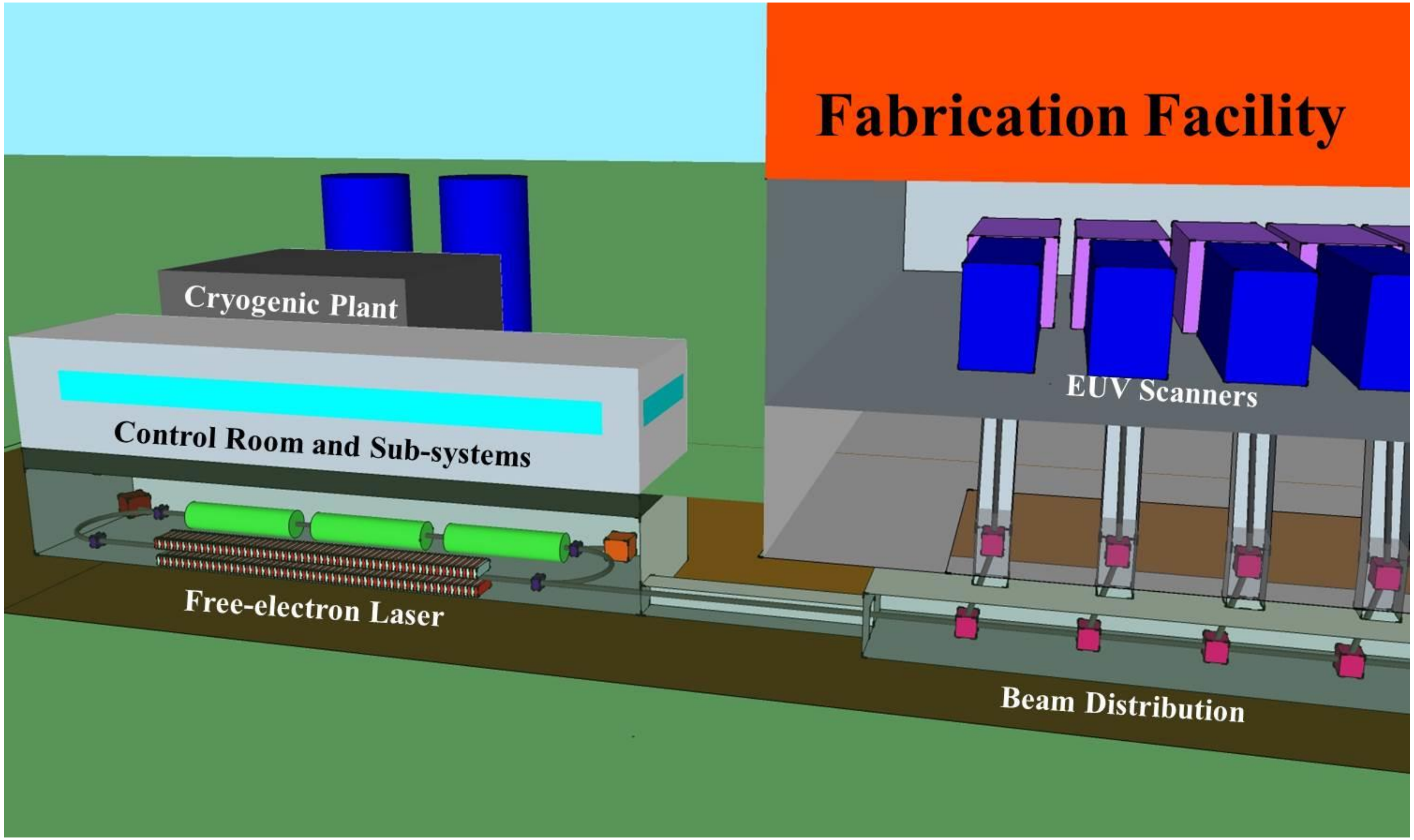
E.R. Hosler, O.R. Wood and M.E Preil. International EUVL Symposium. Maastrict, Netherlands. 2015.

Evolutionary Thinking: Research oriented to industrial FELs

- Single user → Multi-end stations
- High peak power → High average power
- Radiation permits → Minimize radiation
- Many applications and extendibility → Single purpose and power scaling
- Upgrades and scheduled maintenance blocks → predictable, short service
- Constant facility development → First Time Right Design
- Value of the science vs. tax dollars → Wafer cost

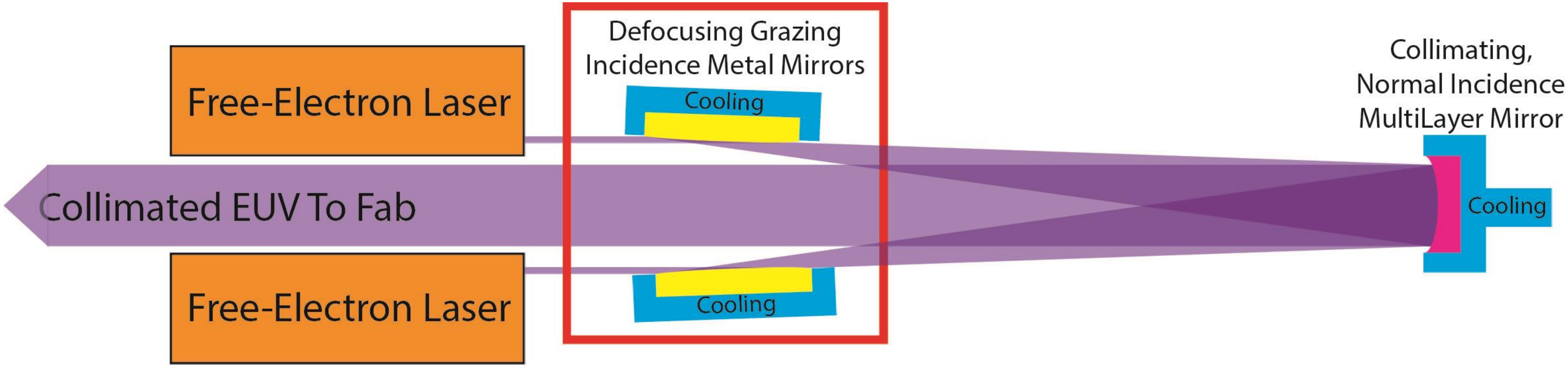
- **How many more can we think of…?**

Fab Integration



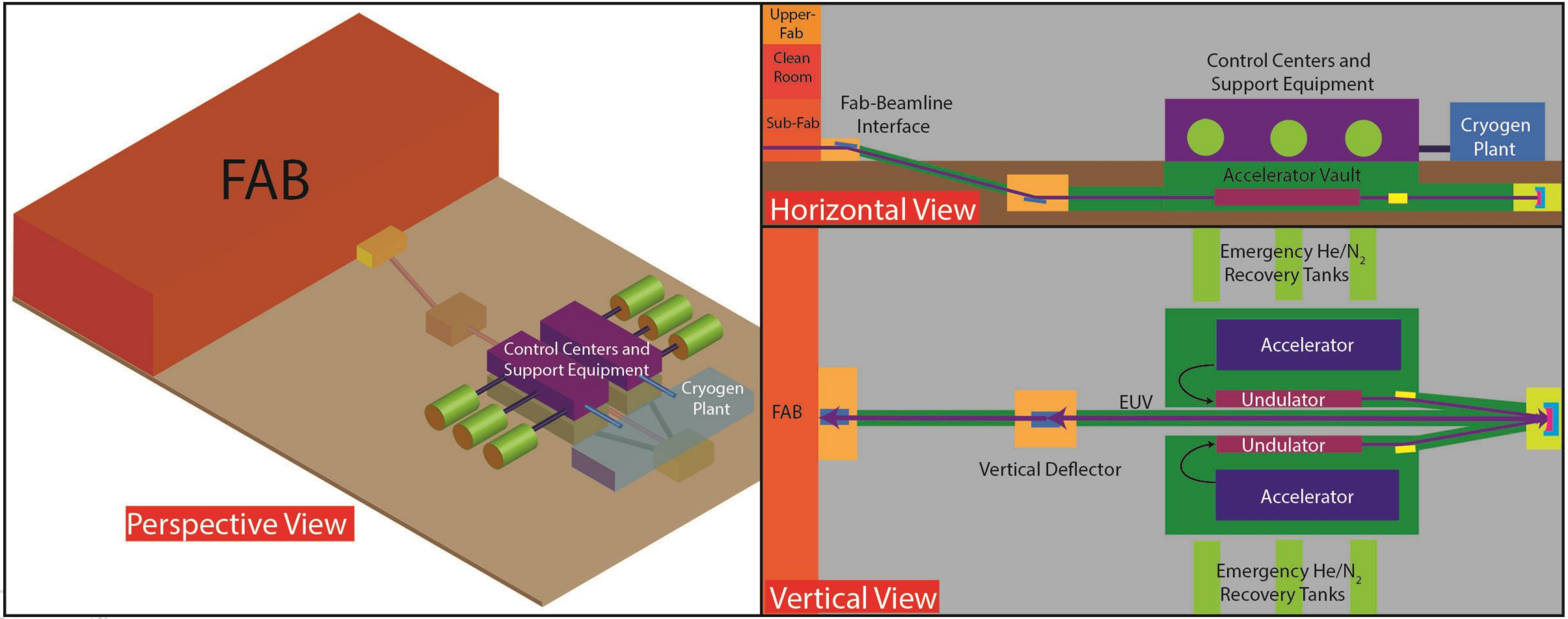
E.R. Hosler, O.R. Wood and M.E Preil. Extending extreme-UV lithography technology. SPIE Newsroom. 2016.

Redundant Operation



Method, apparatus and system for using free-electron laser compatible EUV beam for semiconductor wafer processing. US Patent Number 9,392,679 B2. Granted July 12, 2016.

Redundant Operation



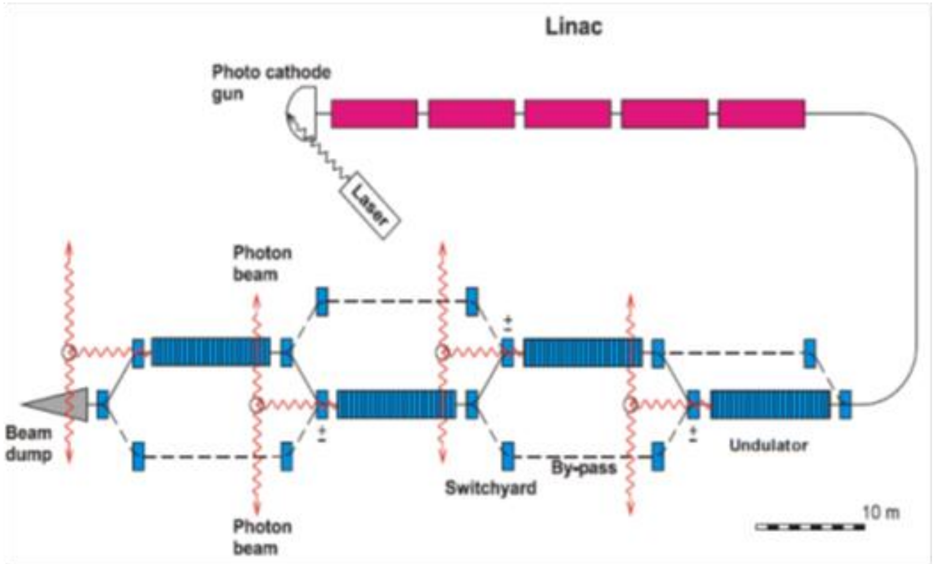
Method, apparatus and system for using free-electron laser compatible EUV beam for semiconductor wafer processing. US Patent Number 9,392,679 B2. Granted July 12, 2016.

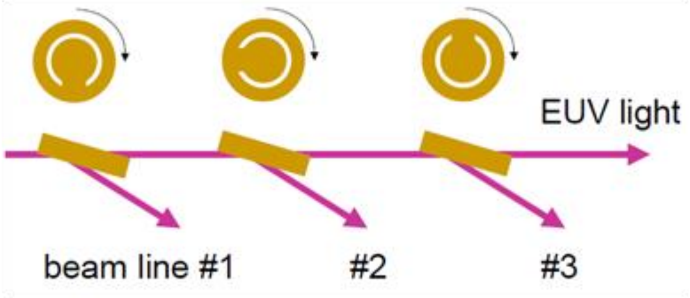
Energy Distribution: Option 1 - Photons

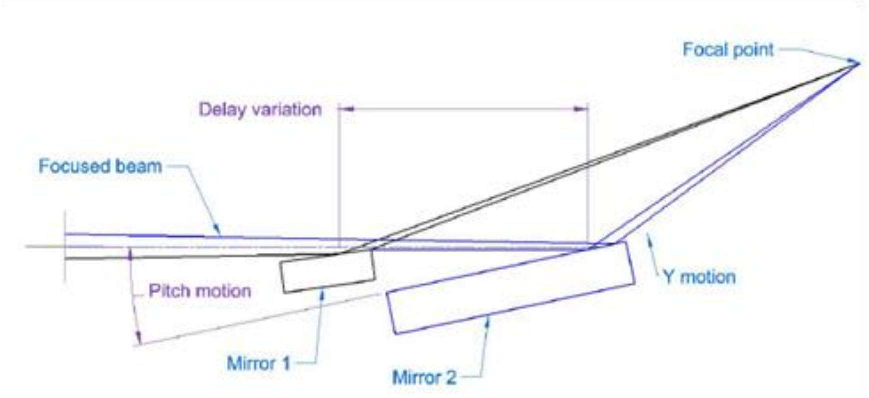
- 10x scanner to power…efficiency of beam distribution system may be the limiting factor
  - 10x scanners @ 1kW each
  - Beam distribution is 20% efficient…
    - 50kW required @ FEL output

- Multiple schemes proposed…

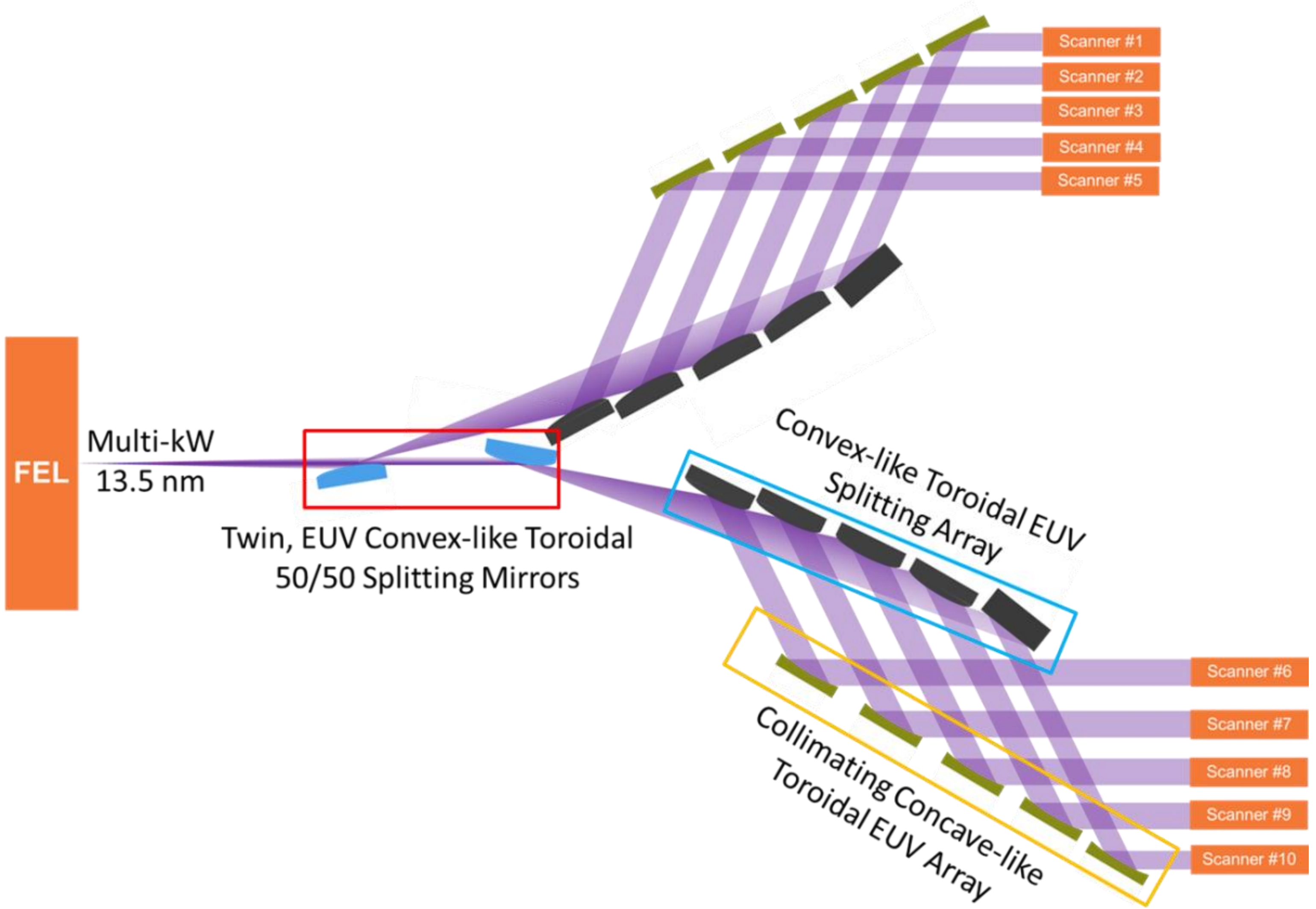
- Is there an optics-only solution?
- Is there a solution for the electron beam?





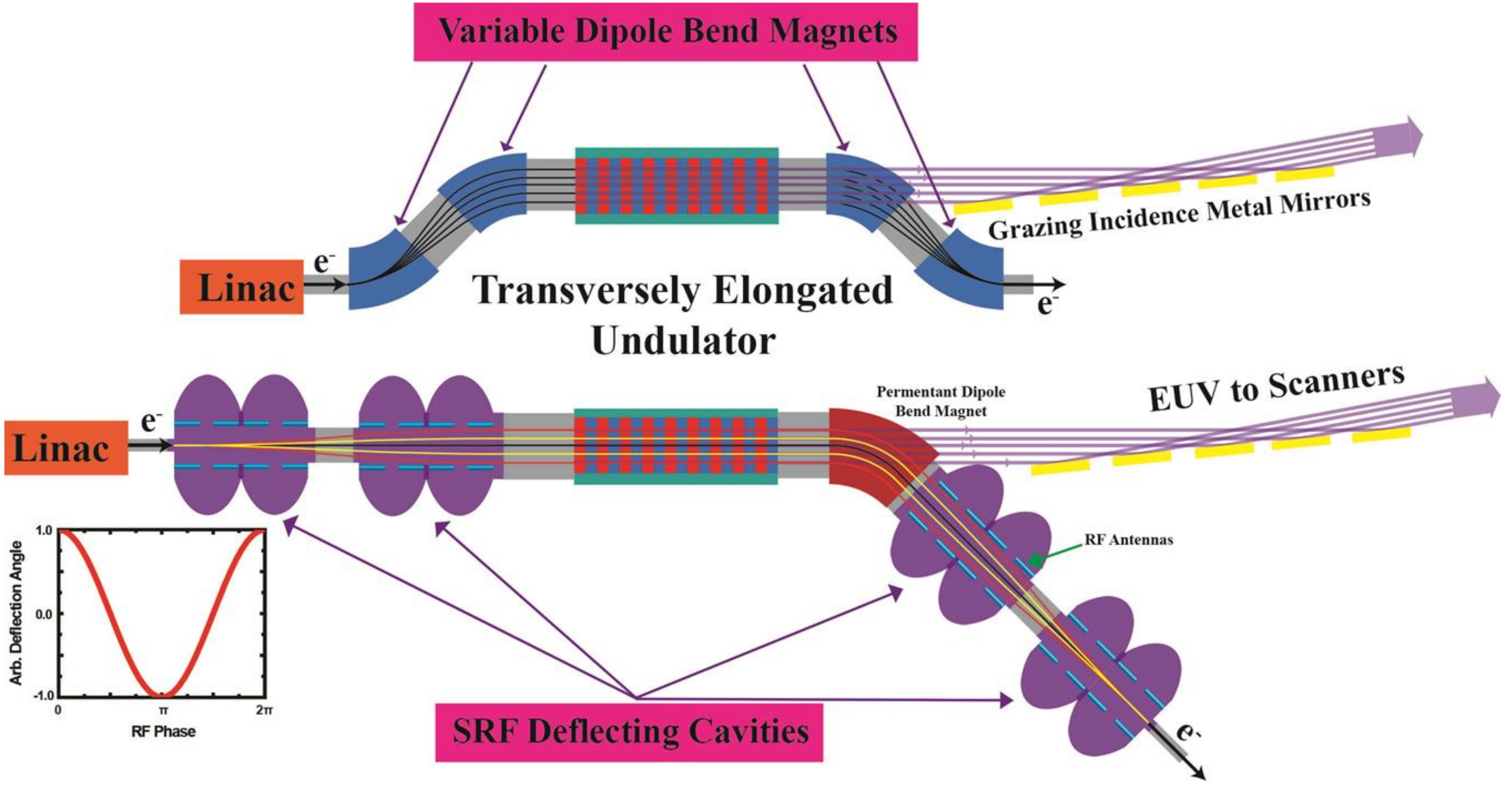


Energy Distribution: Option 1 - Photons



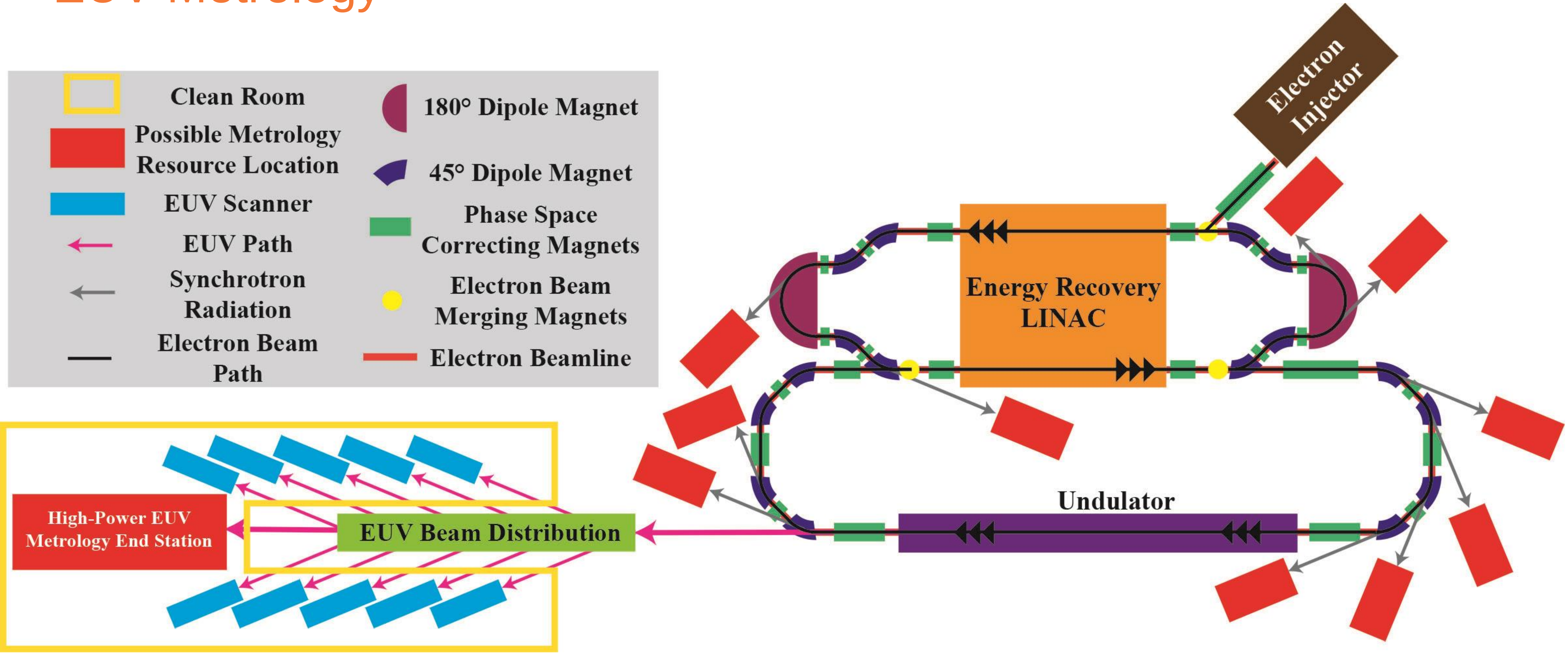
Hosler, E.R., Patent Filed 2015.

Energy Distribution: Option 2 - Electrons



Hosler, E.R., Patent Filed 2015.

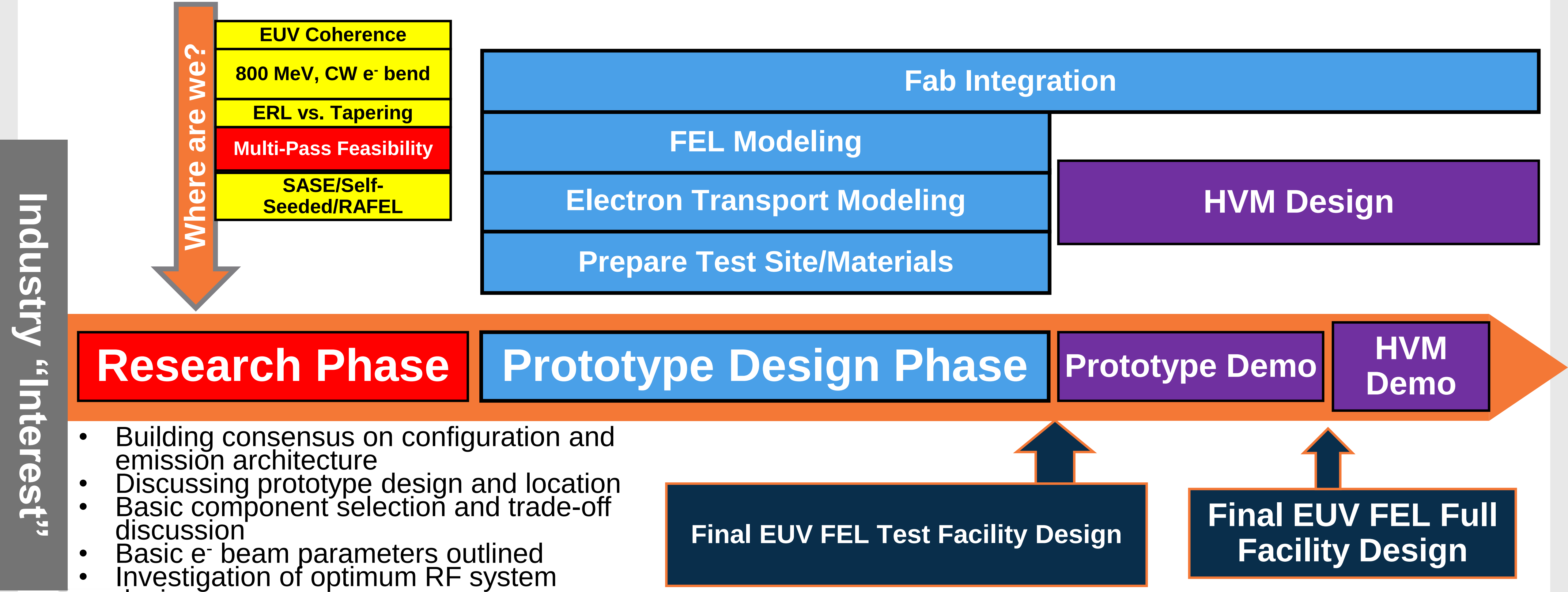
EUV Metrology



Hosler, E.R., Patent Filed 2015.

Summary

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

Final EUV FEL Test Facility Design

Final EUV FEL Full Facility Design

- 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

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.

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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