

An Accelerated Future

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FEL 2024

The opportunity is *now*

and only now to convert the FEL community to an industry.

Disclaimer

I may or may not hold financial positions or interests in the companies I am about to discuss.



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SECURITY AT THE SILICON LEVEL

EUV Lithography – Smaller is Better



Courtesy of ASML

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

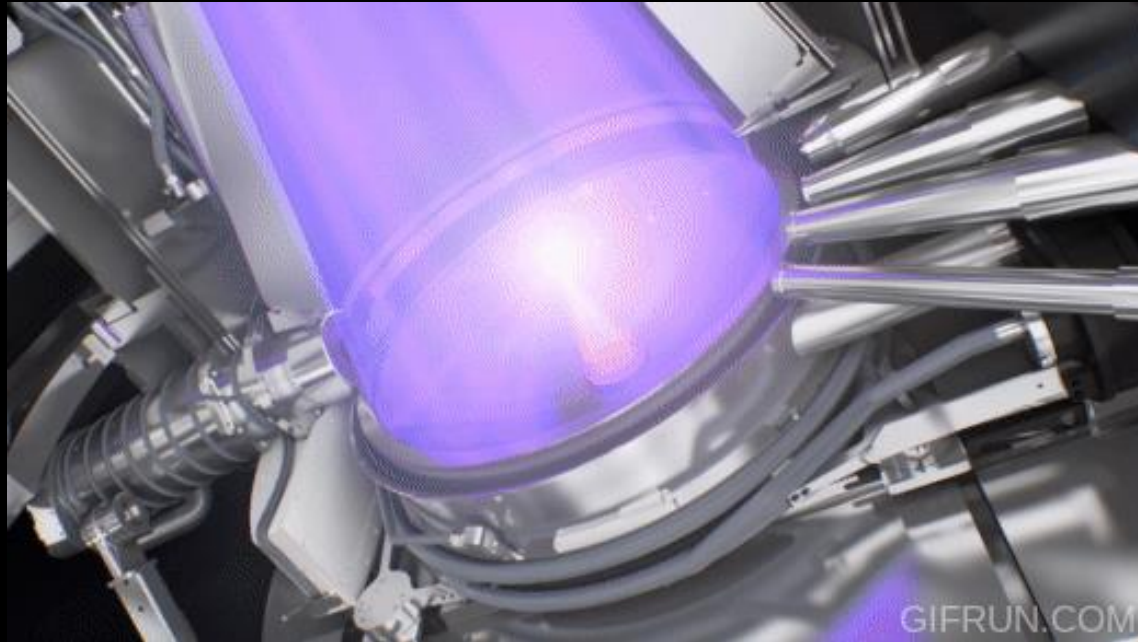


CIFRUM.COM



Creating 13.5nm Light

- Laser-Produced Plasma - LPP



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Brief, Relevant History of EUV

- 1999/2000: EUV LLC and "On the floor in '04"
- 2009: First Full-Field Scanners, i.e. 300mm Ready
- 2011 & 2013: NXE:3100 and 3300s
- 2018: EUV in HVM (SEC, TSMC)
- 2025: EUV High-NA Introduction



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...Can we do something else?



Brief, Relevant History of Accelerators

- 2008: LCLS
- 2011: Semiconductor Industry Study + Academic Papers★
- 2014: Earnest Development of EUV-FEL Integration★
- 2022/23: XFEL and LCLS-II
- 2021-2023: Founding xLight, Substrate, Inversion, Tau, etc.?★



And now we're here...

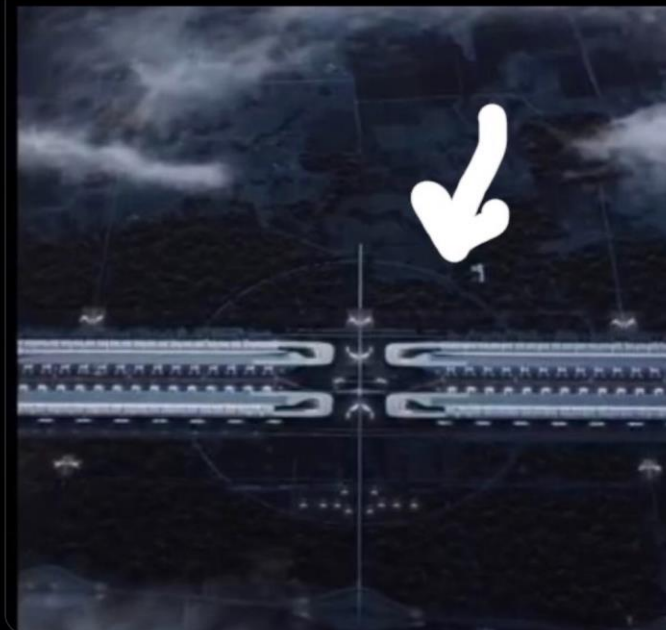


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Looks like a synchrotron - Elon going to build free electron laser based EUV machine?

Holy Giga based 🤖🧠🔥

joshua steinman (🇺🇸, 🇺🇸) @JoshuaSteinman · 12h
Is there a particle accelerator underneath?? x.com/elonmusk/status...



45 65 1.2K 152K

Elon Musk (🇺🇸, 🇺🇸) @elonmusk

Subscribe

FEL FTW

Semiconductor Manufacturing

Photolithography



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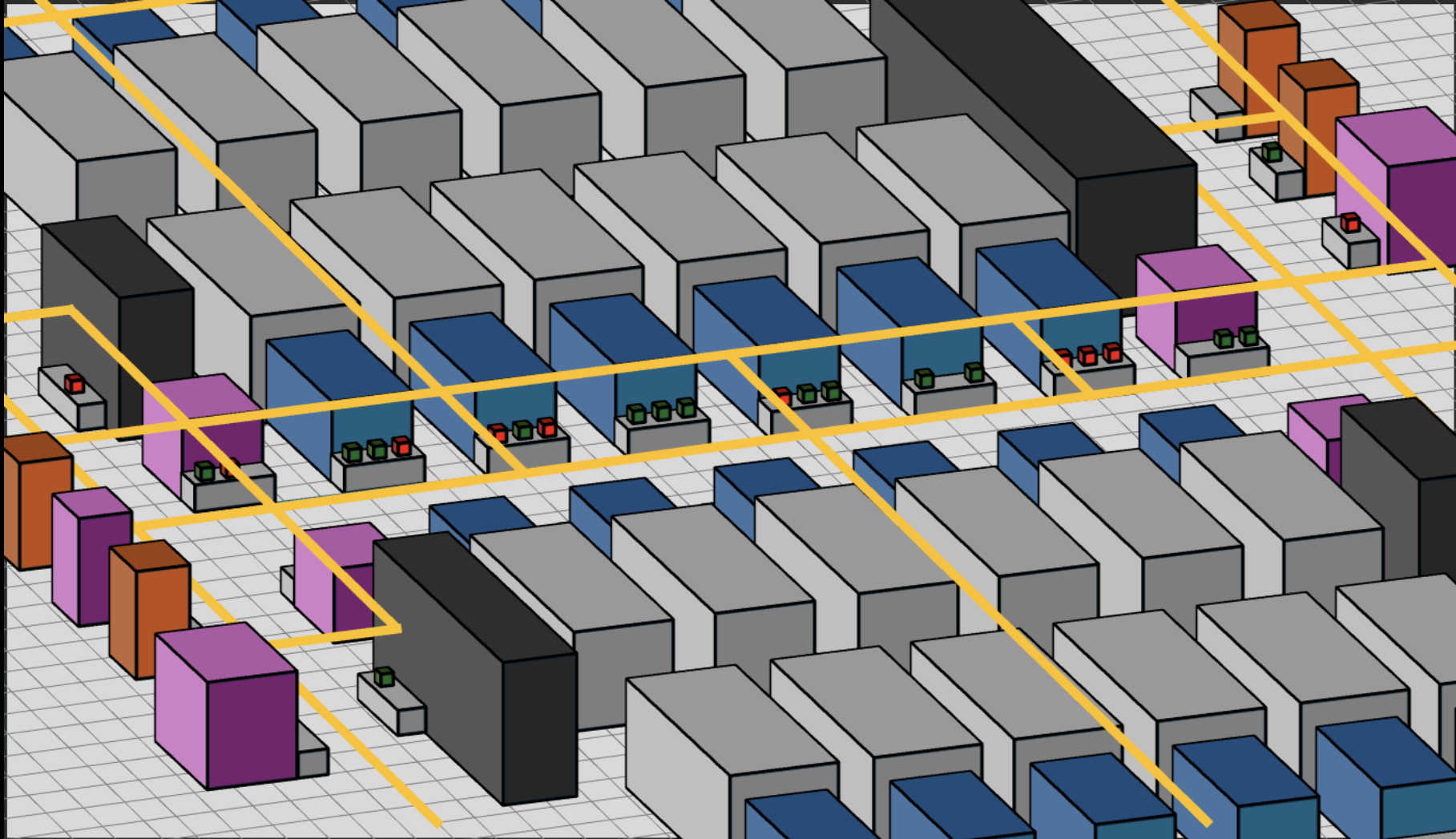
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Fab to Datacenter

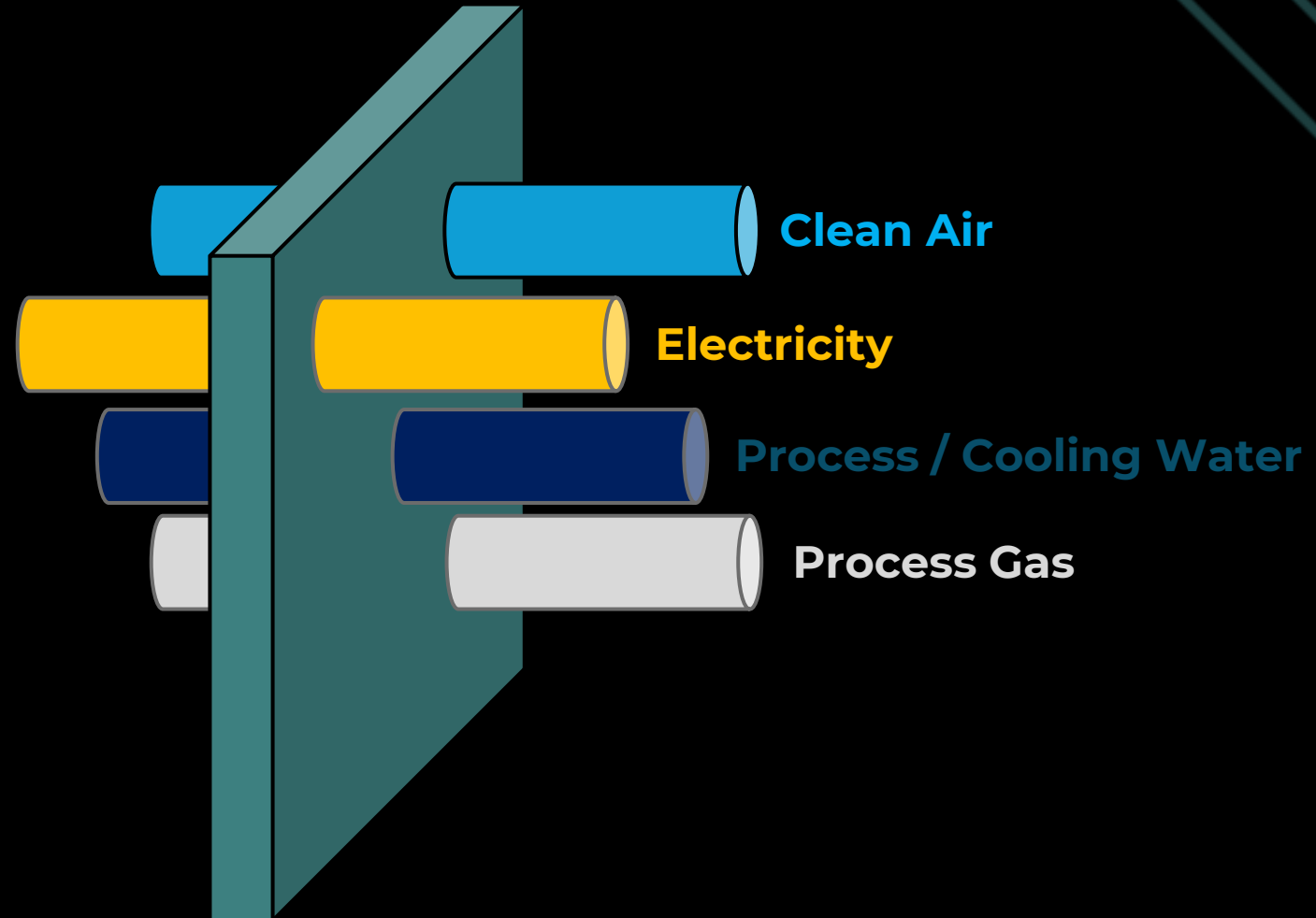


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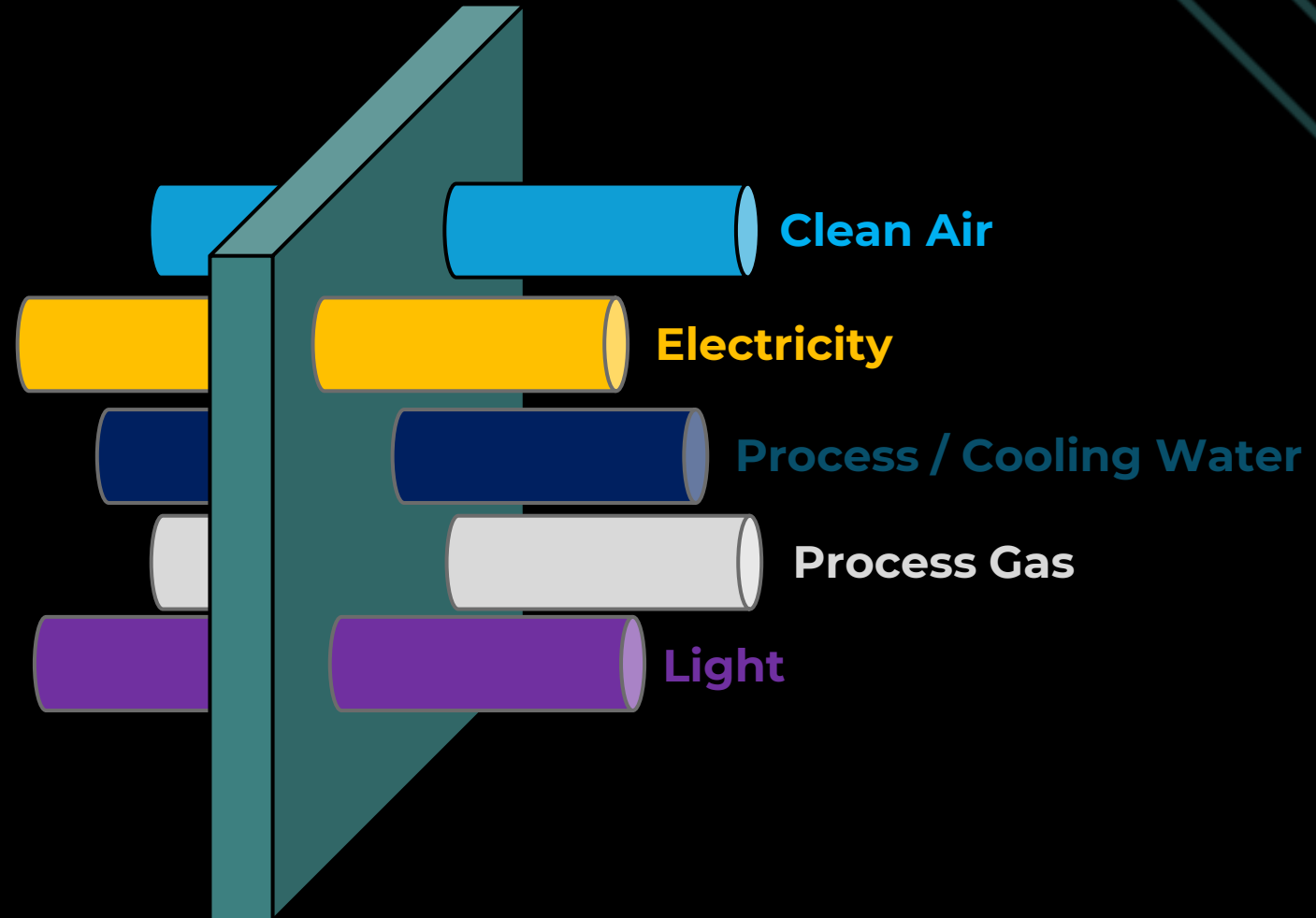
Fab Layout



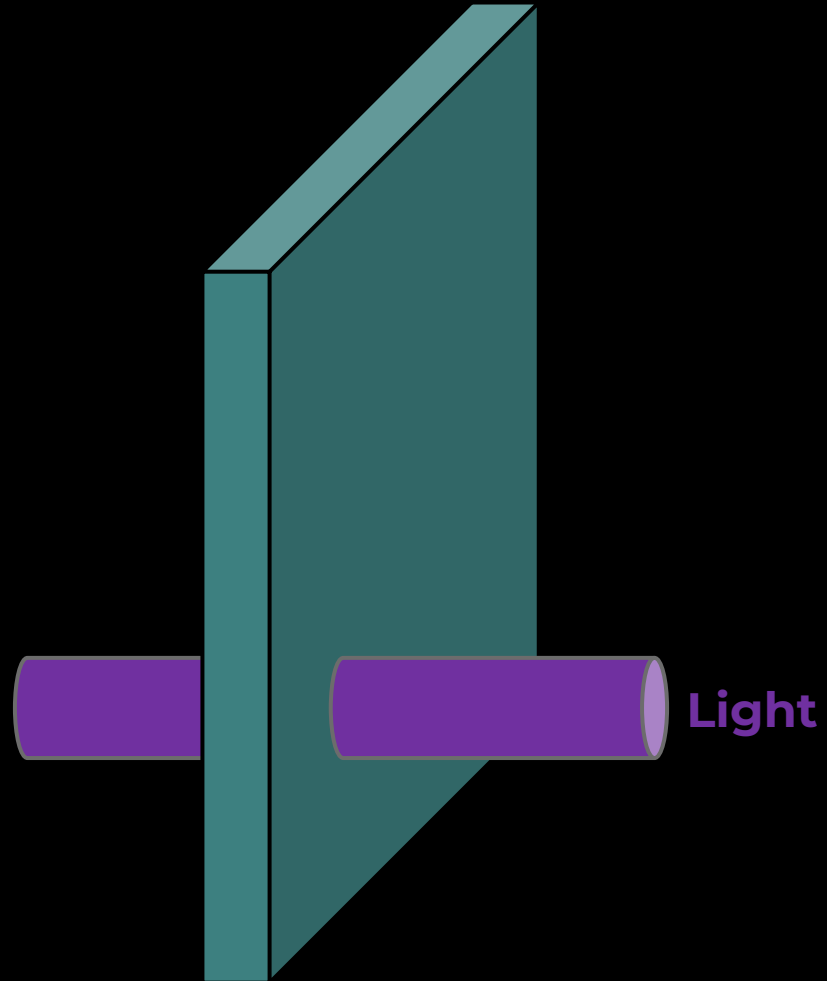
The Paradigm



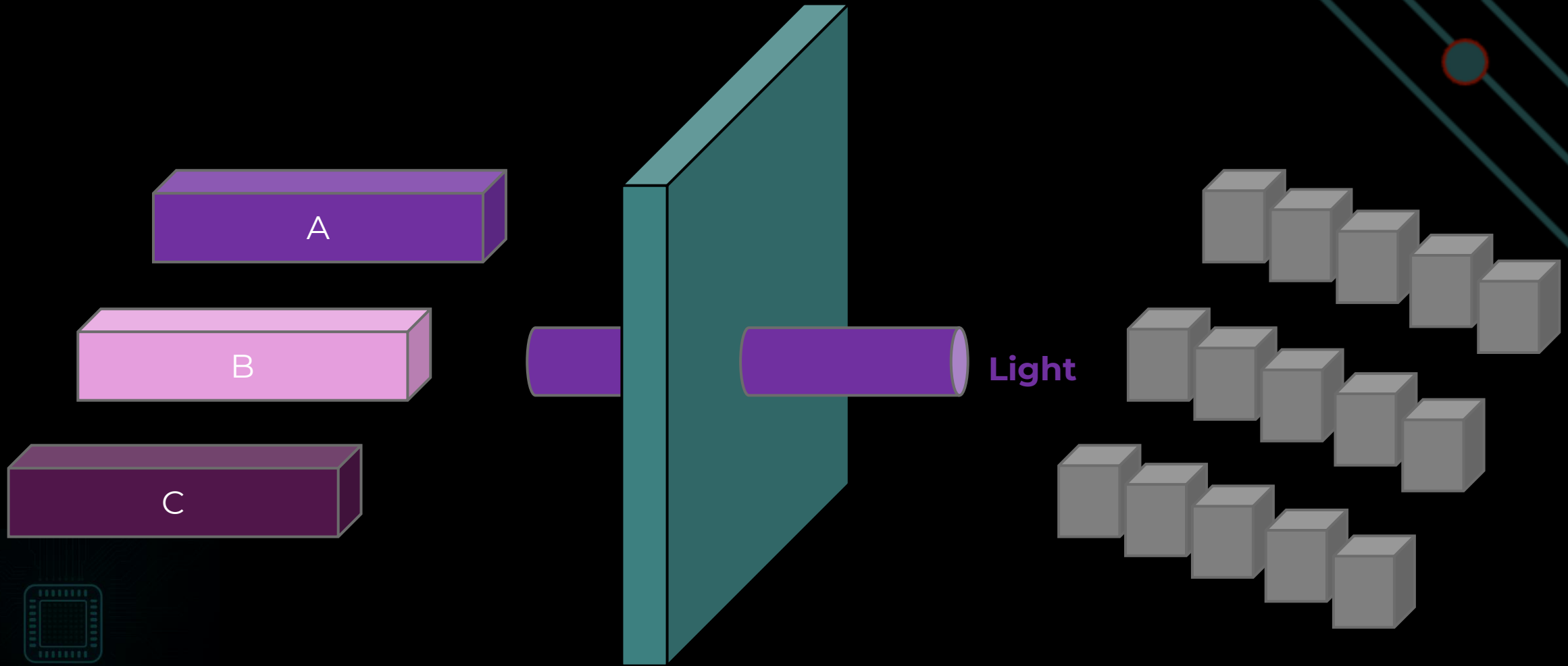
The New Paradigm



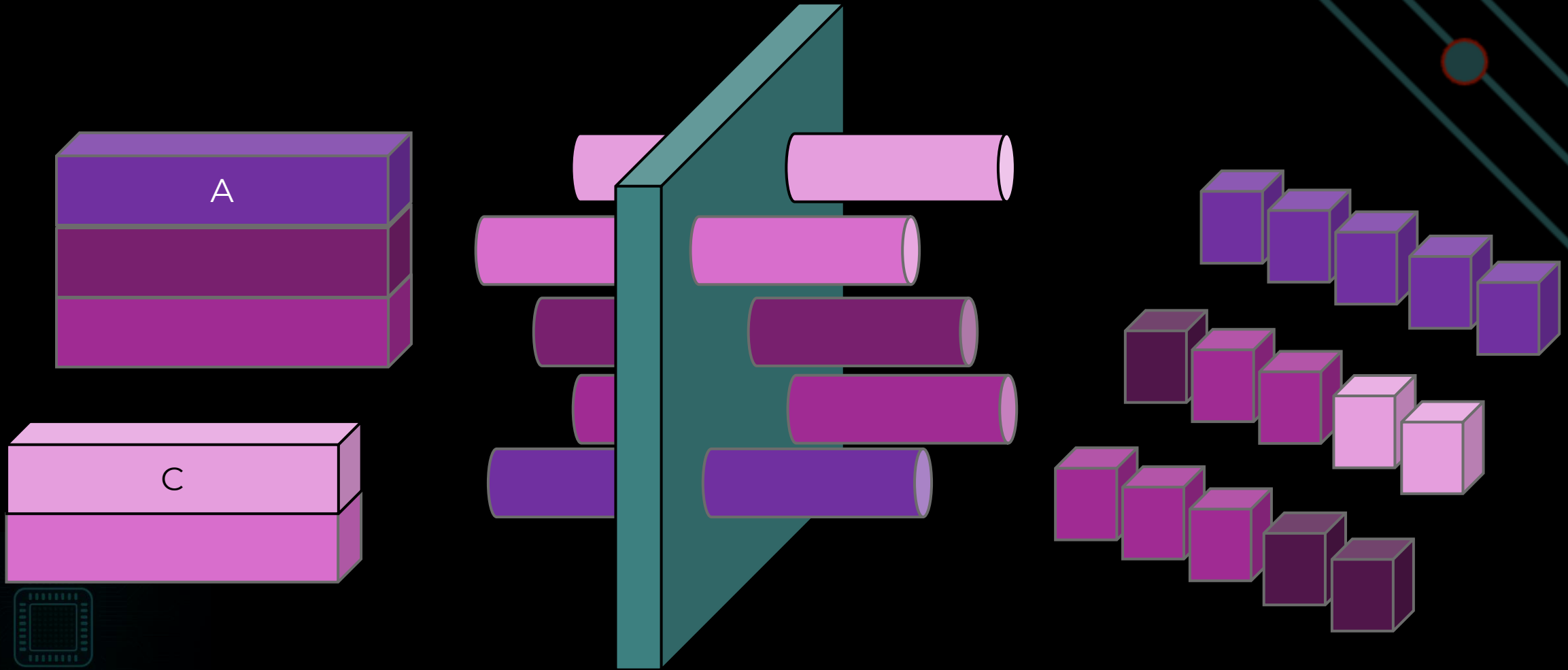
Light as a Utility



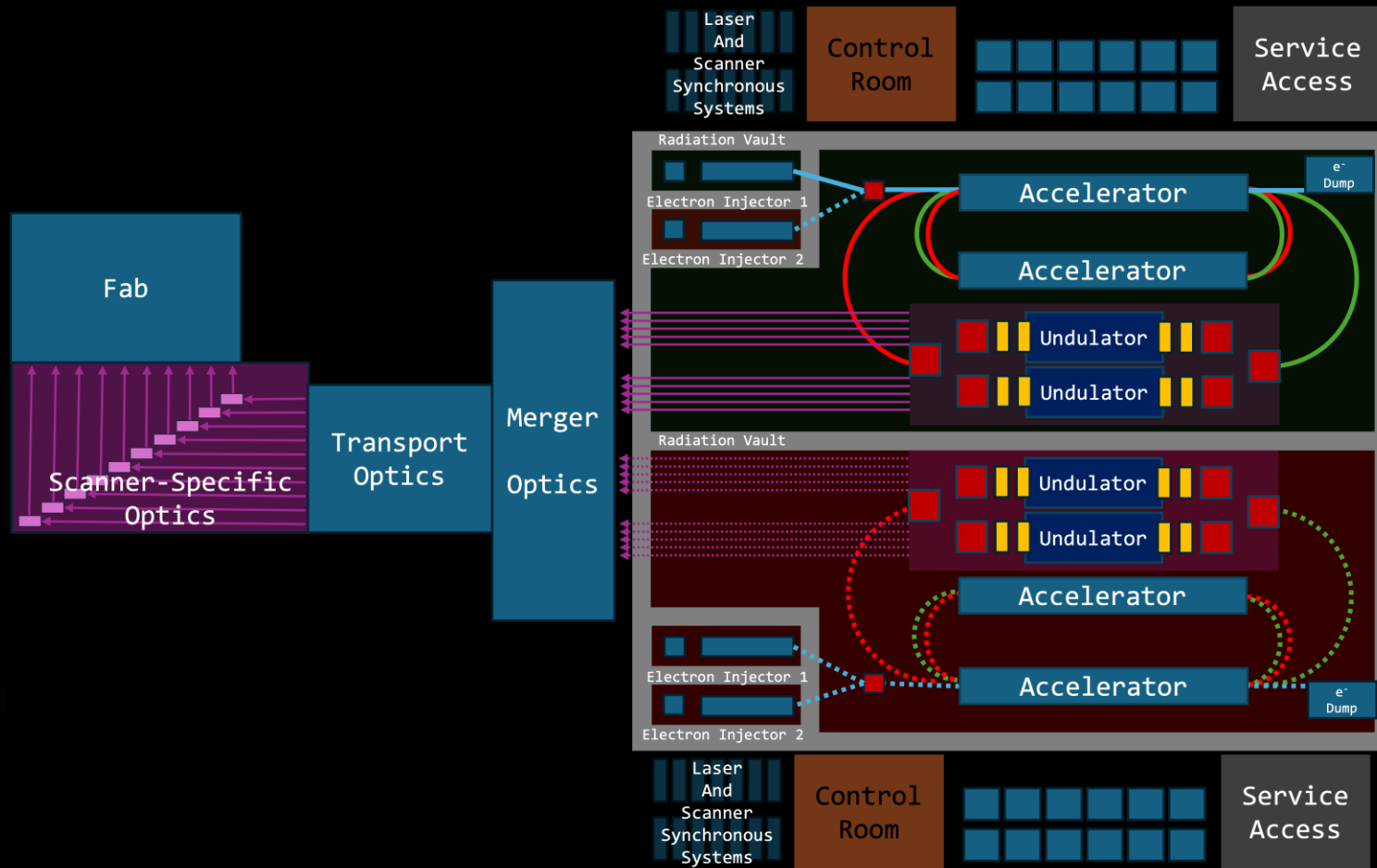
Light as a Utility



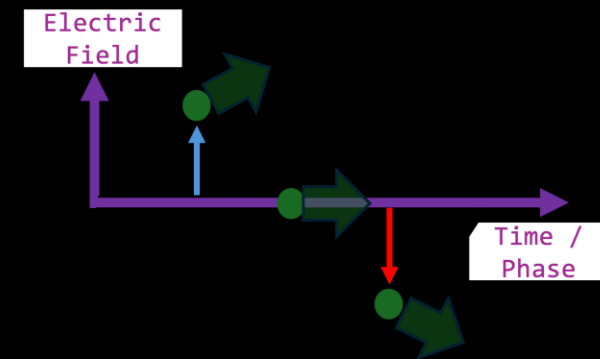
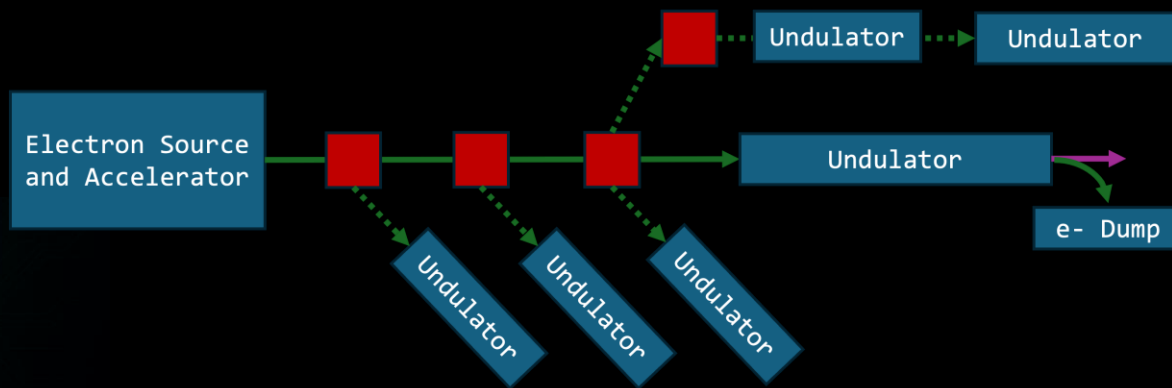
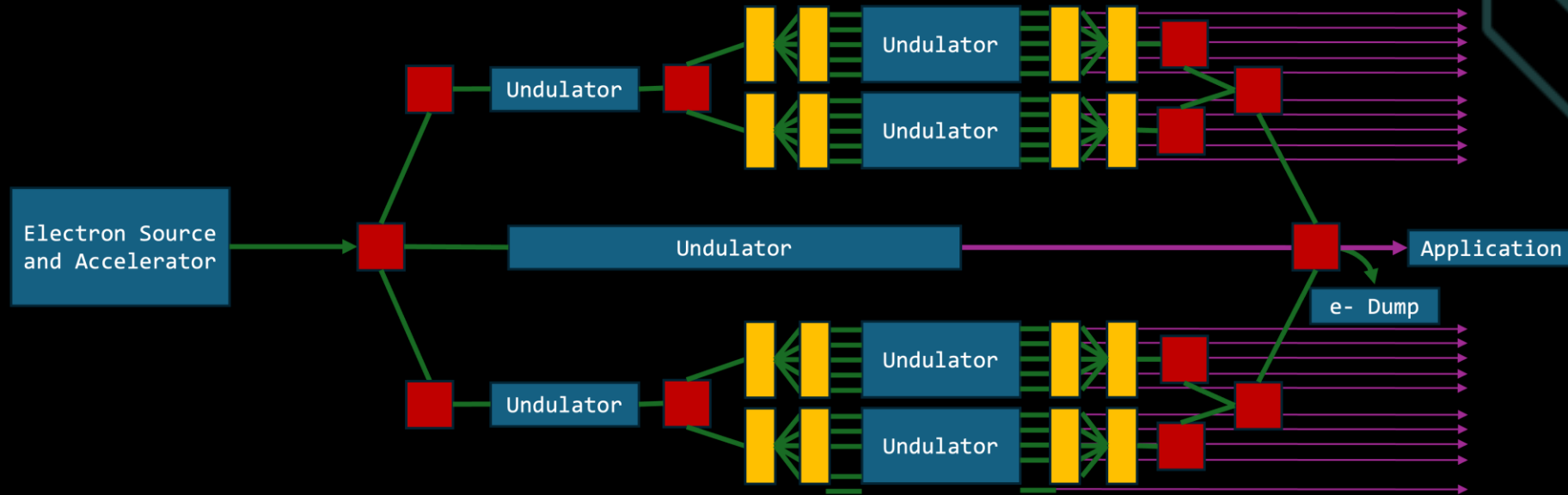
Beams as a Utility



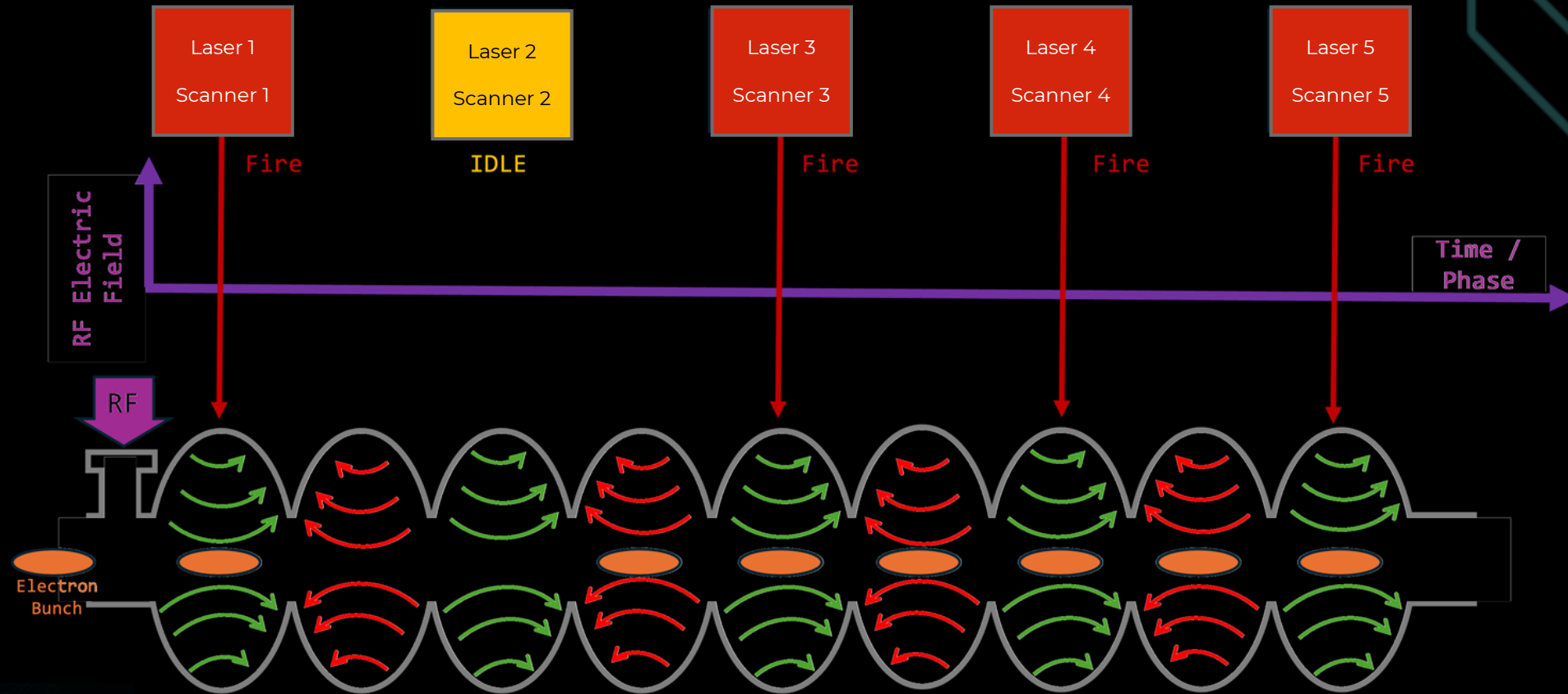
Fab Integration



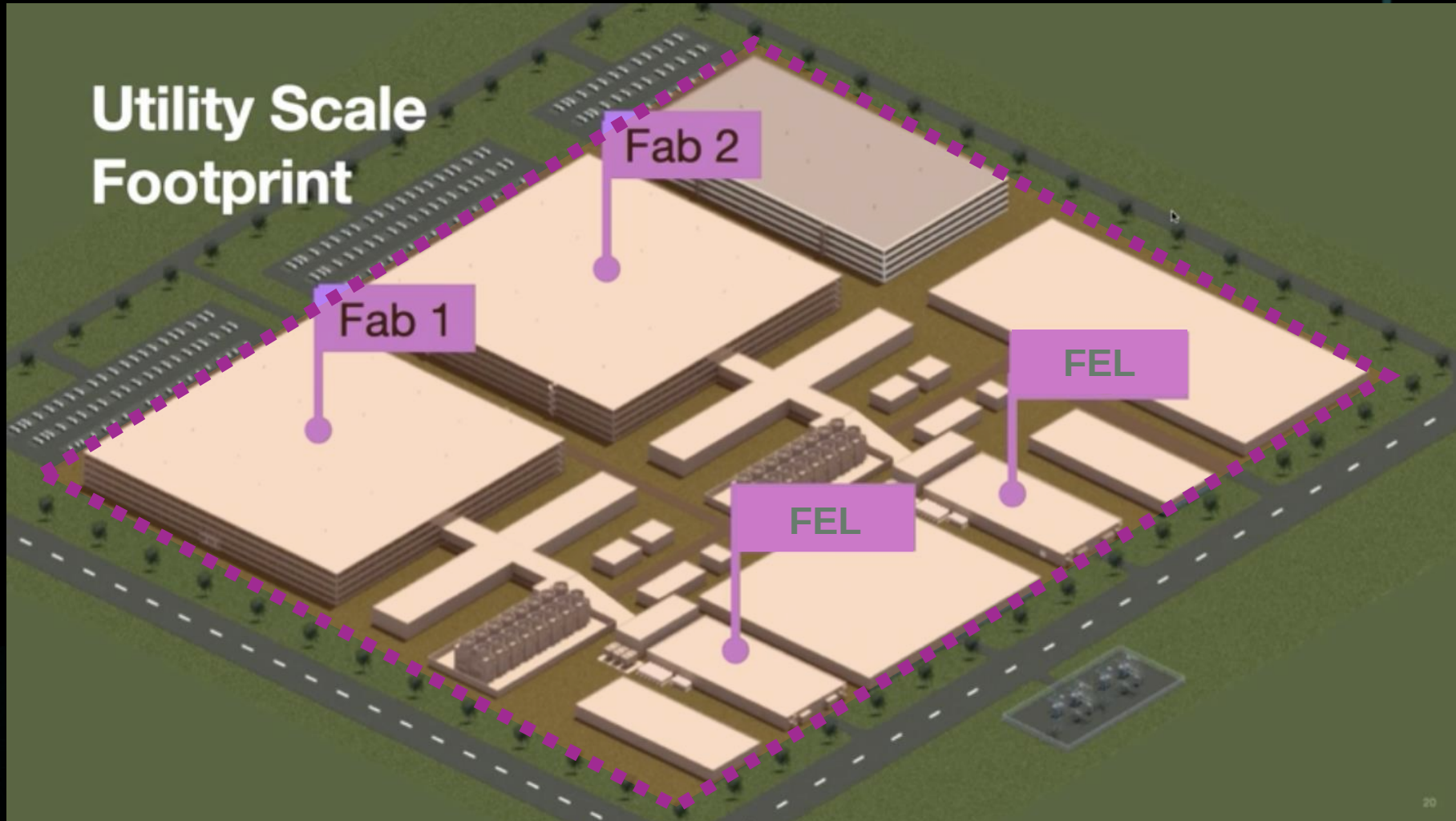
Electron Multiplexing - Switchyards



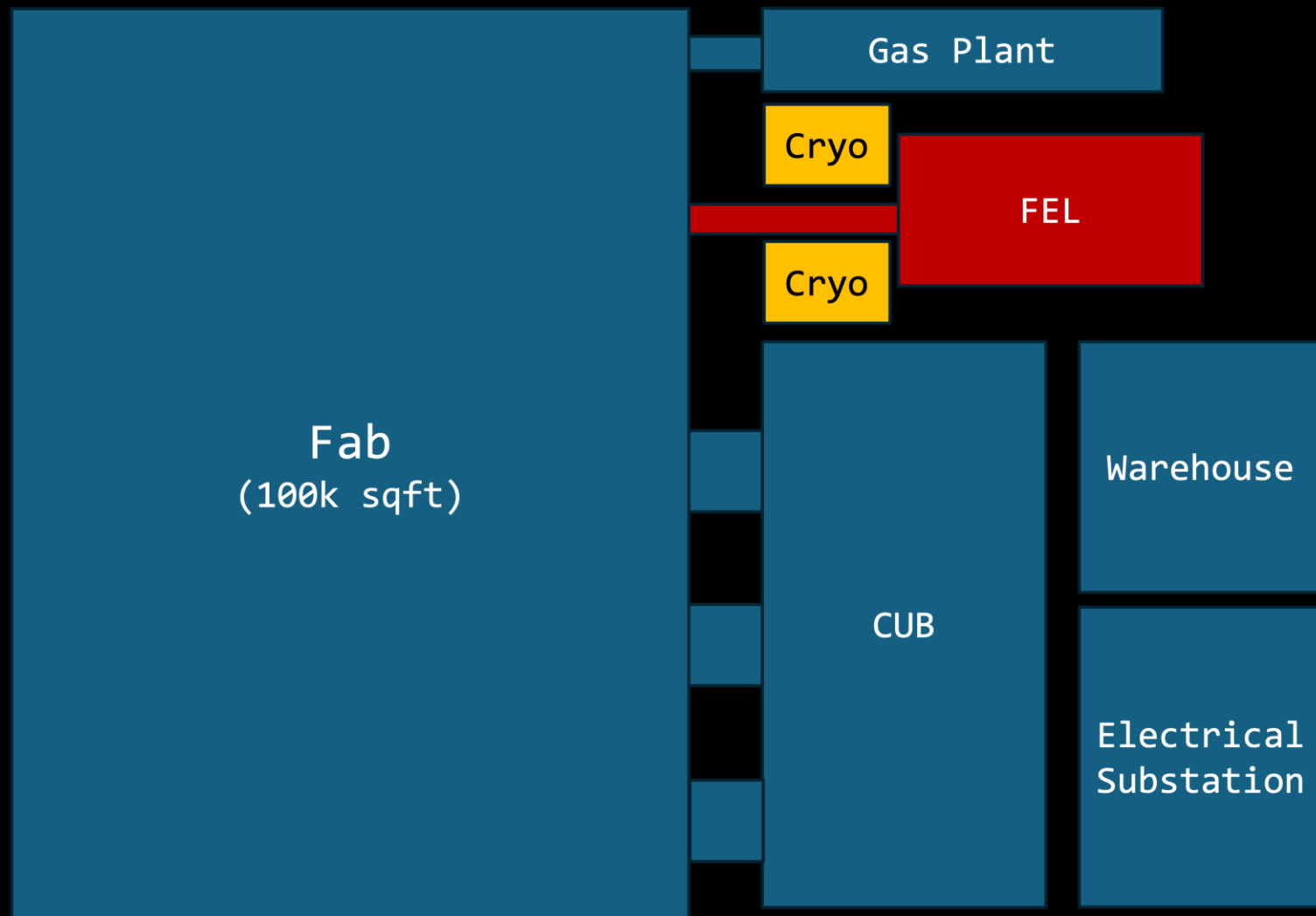
Complexity in LINAC Operation



Semiconductor Manufacturing Implications



Just Another Box

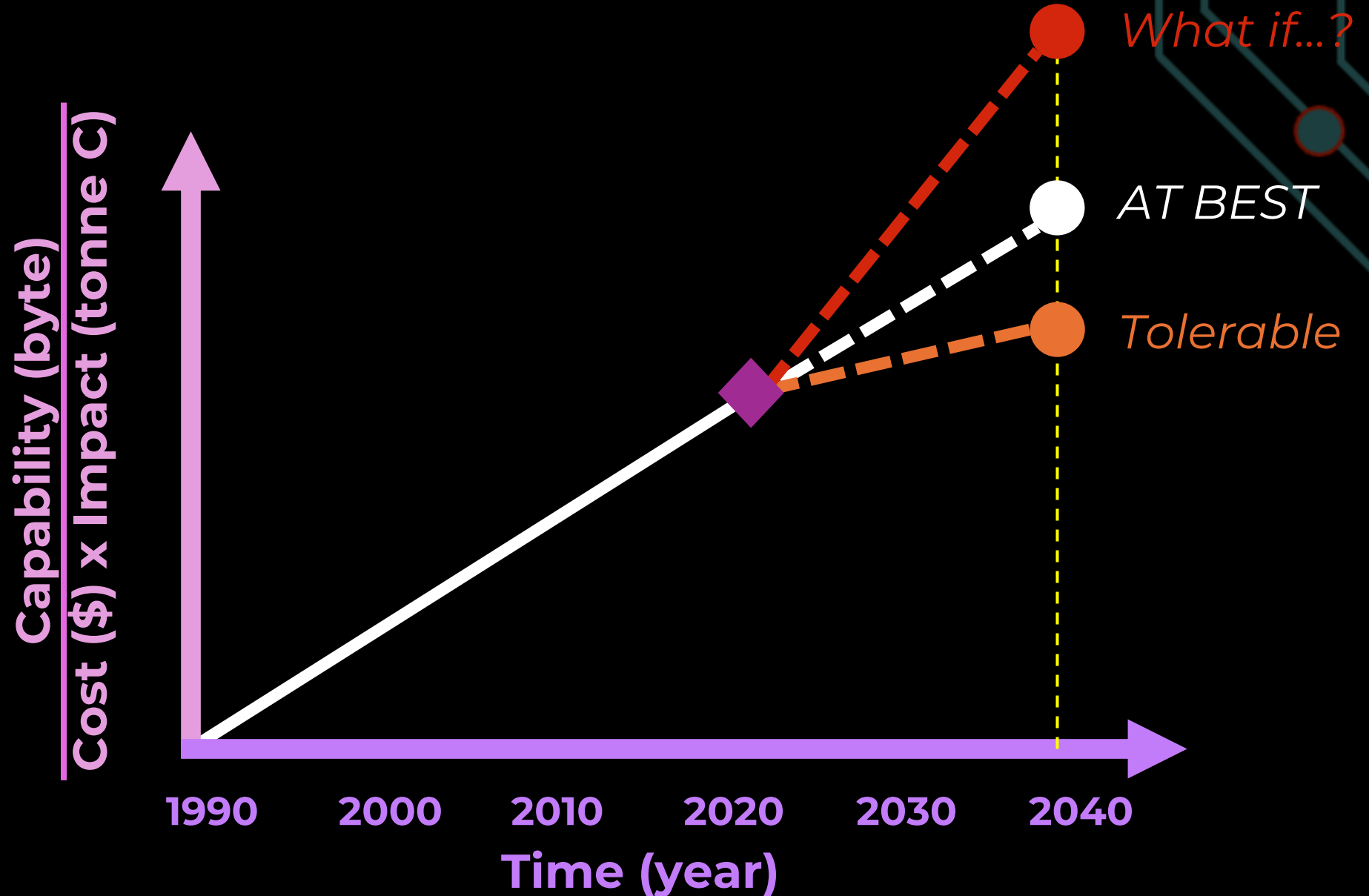


Next Generation Lithography

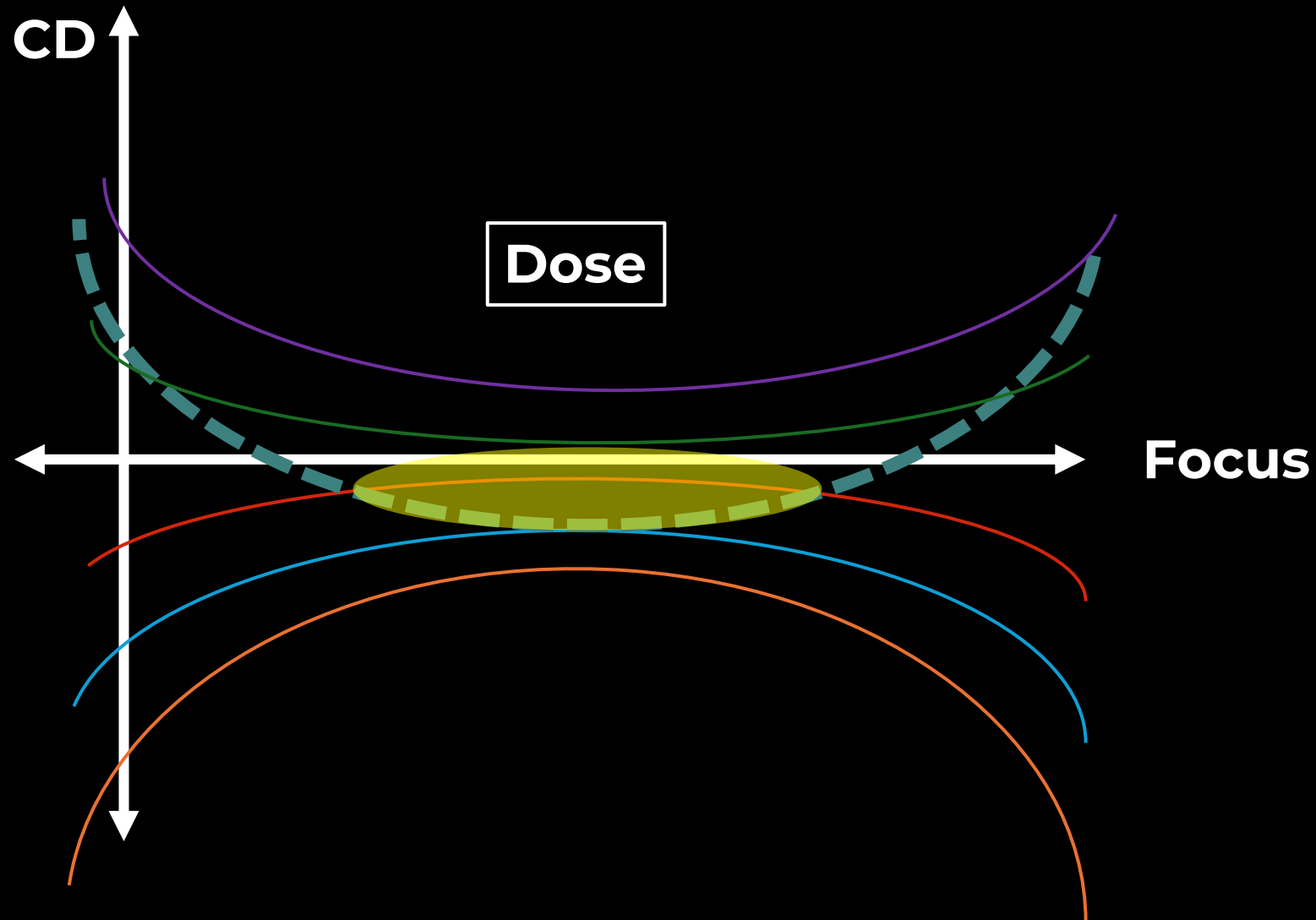


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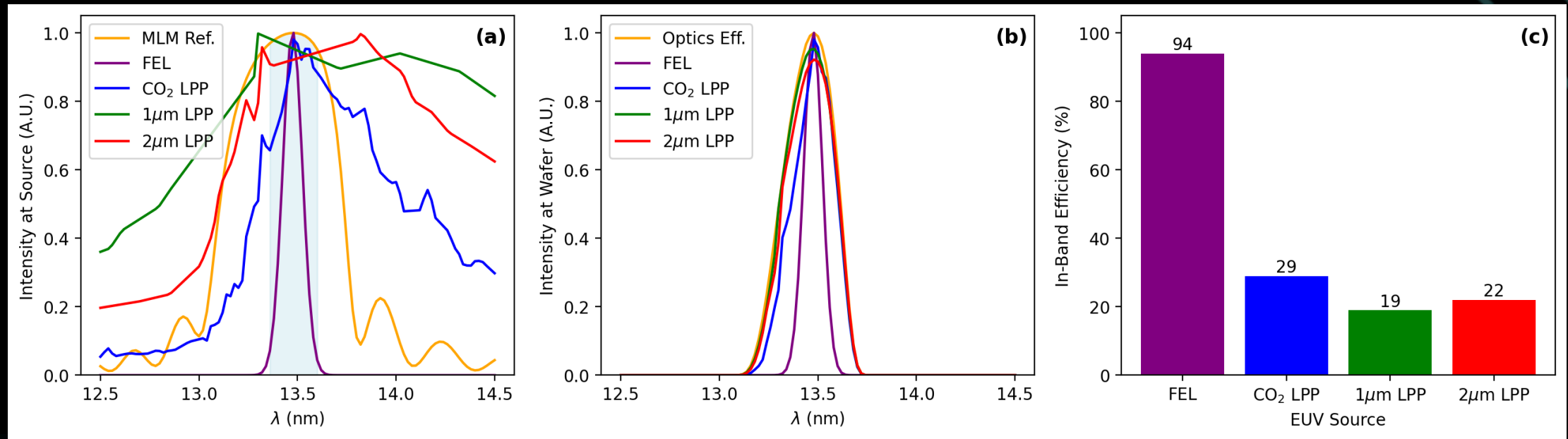
Triple Constraint Drives Innovation



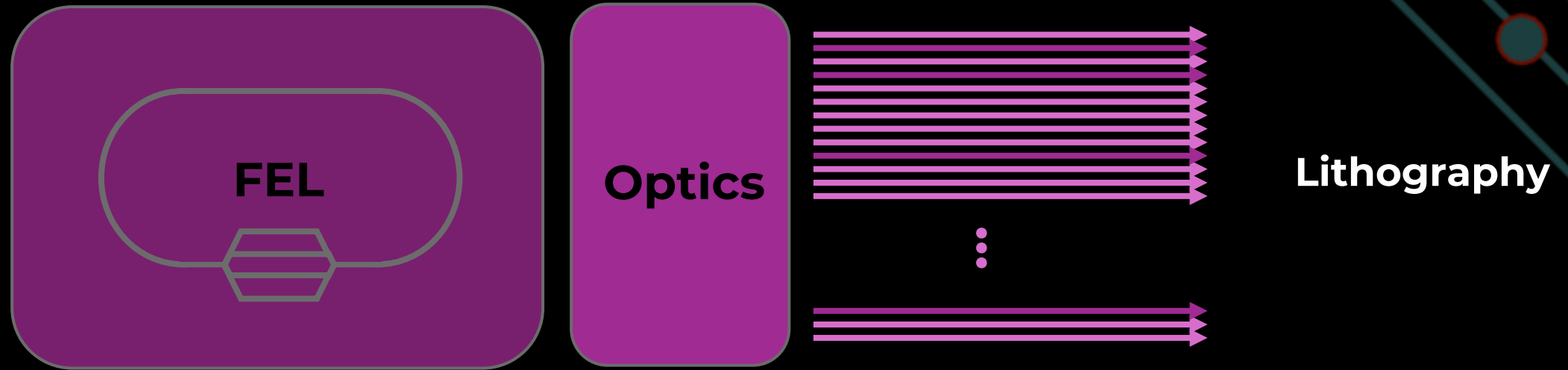
Lithography Process Window



Bandwidth



Light as a Utility

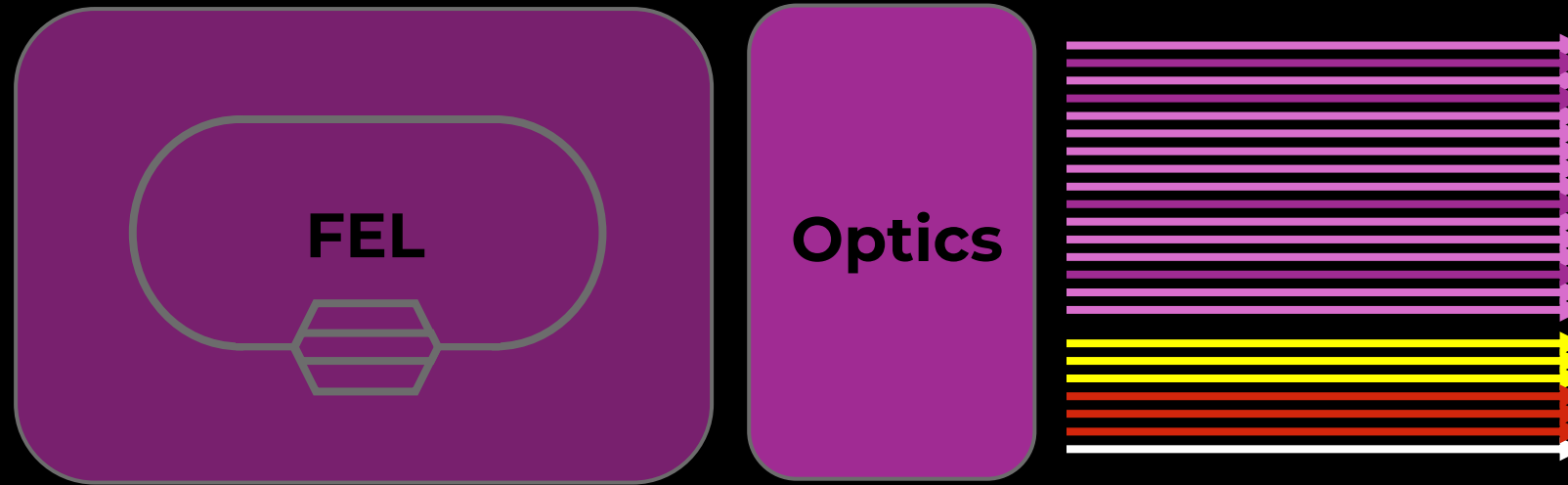


Why new wavelengths? (3.1nm)

- Resolution $CD = k_1 \frac{\lambda}{NA}$
- Depth of Focus $DOF = k_2 \frac{\lambda}{NA^2}$
- Pupil Optimization – 3-beam imaging, etc.



Light as a Utility



Lithography

Metrology / Inspection

Undulator Terms

Output Wavelength

$$\lambda_R = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

Electron Energy



Age of Accelerator Industrialization



Current state of the ecosystem

Project-To-Project

- XFEL, LCLS-II, ... EIC, FCC

Vendor Specific Ramps, Transition to Alternative Markets

Electron Guns
Accelerator Cavities
Undulators
Electron Dumps

Control Systems
Cryogenics
Magnets
Heavy Industry



Accelerator Ramp for Lithography

- 60-100x EUV Scanners Deployed per Year
- 10-20 Scanners per EUV Accelerator



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5-10x GeV-class
Accelerators per Year



Picks and Shovels

Industrialization Status

Electron Guns / Lasers	Control Systems
Accelerator Cavities	Cryogenics
Undulators	Magnets
Electron Dumps	Heavy Industry



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Picks and Shovels

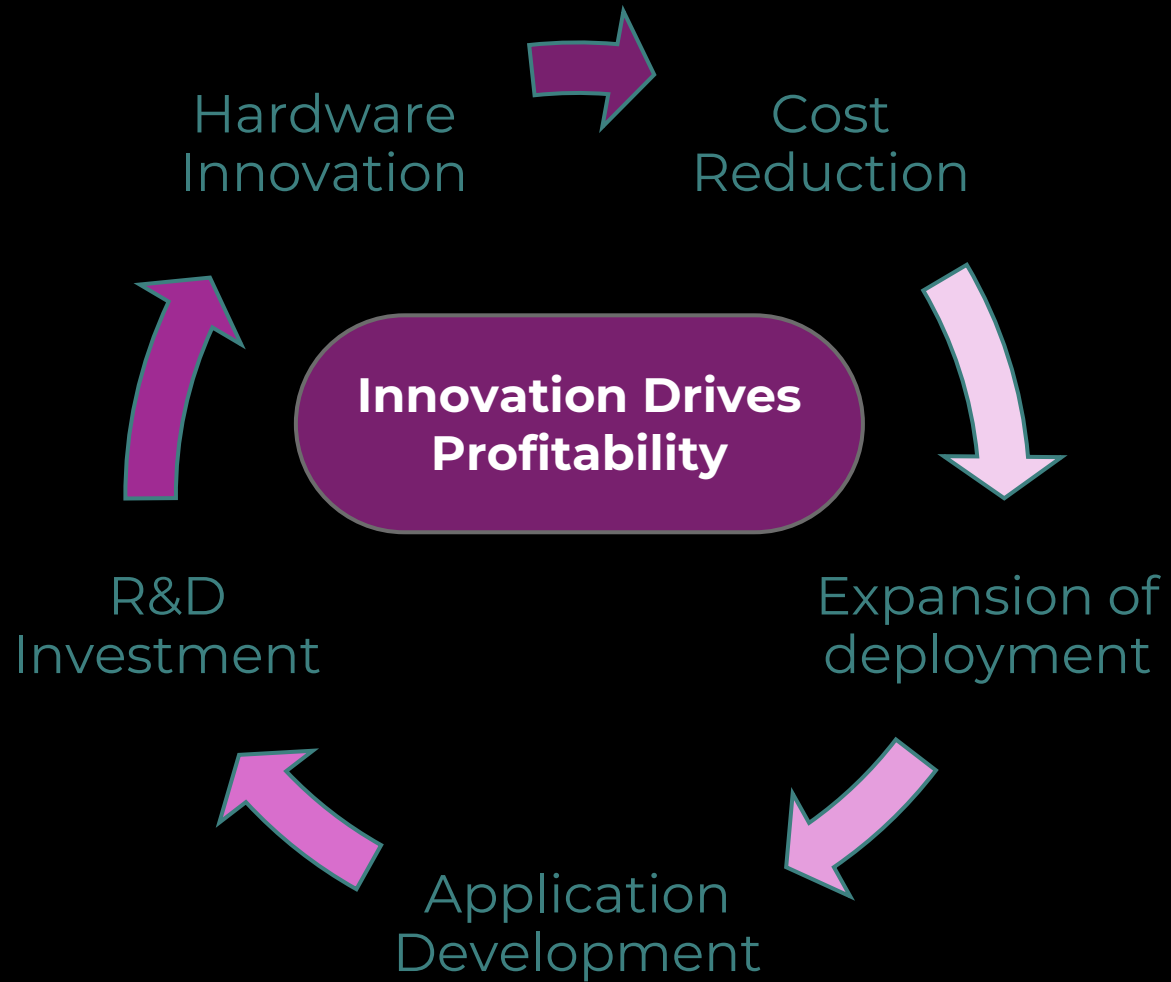
Industrialization Status

Electron Guns / Lasers	Control Systems
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Consortia Driven
Manufacturing Facility



Effect of Industrialization



A New Industry

Criticality in Application, Breadth and Depth, and Cost



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The Window is Closing

