OPPORTUNITIES FOR INDUSTRIAL ACCELERATORS FOR SEMICONDUCTORS

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Libera Workshop, 14 May 2025

WHO AM I?

- Currently visiting professor at La Sapienza University in Rome for Spring 2025.
- Accelerator Division Director and Director of the Argonne Accelerator Institute from 2017-2024
  - Led the accelerator team for operations of the Advanced Photon Source and made major contributions to the APS Upgrade, a 4th gen storage ring light source commissioned in April 2024 and now in operation.
- Head of the Center for Beam Physics/Berkeley Accelerator Controls and Instrumentation at Berkeley Lab from 2003-2017
  - Led a group of scientists and engineers developing leading concepts and technology for a wide variety of accelerators
- Advanced Light Source Accelerator Physics 1996-2003
  - Worked on feedback systems to control multibunch instabilities. First observation of coherent synchrotron radiation from a storage ring. Built harmonic RF system to lengthen bunches.
- Center for Beam Physics, Berkeley Lab 1991-1996
  - Contributed to design of feedback systems for PEP-II collider at SLAC.
- Ph.D in Physics from Cornell University in 1991 working on CESR ring.

WE ARE NOW IN A GOLDEN AGE OF ACCELERATORS

- We are building more new machines around the world than ever before with performance that was only dreamt of a decade ago.
- We can design machines with micron beam sizes and micron stability over kms
- We can measure and control timing jitters down to femtoseconds.

Palmer House Downtown Chicago

Particle accelerators are known mainly for their scientific applications. There are many more applications that can benefit society.

TWO NEW EXCITING APPLICATIONS OF ACCELERATOR TECHNOLOGY IN THE SEMICONDUCTOR INDUSTRY

Lithographic light source:

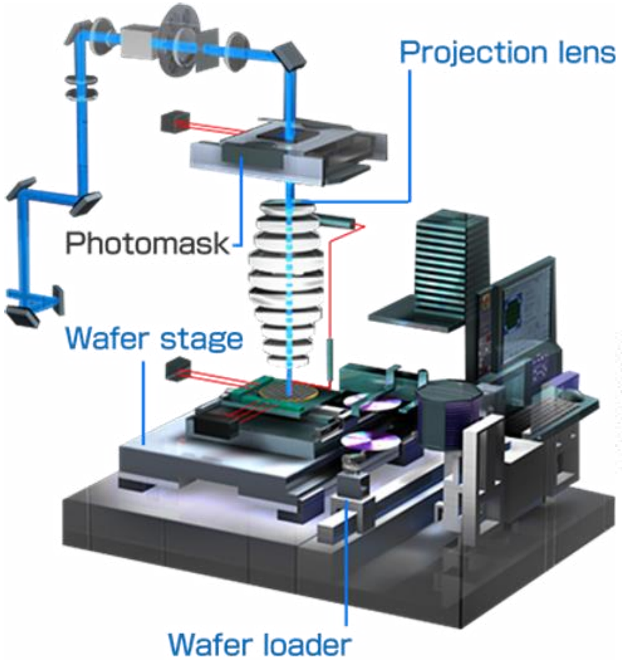
- State-of-the-art lithography introduced in 2016 works at EUV wavelengths, specifically 13.5 nm, that allows for printing of features of a few nm.
- The current light source, the Laser Produced Plasma (LPP), is capable of a several hundred watts but may be limited and is not energy efficient.
- Accelerator-based light sources are very capable of producing light at this wavelength using Free Electron Laser (FEL) technology.
- Several labs and startup companies are exploring this approach.

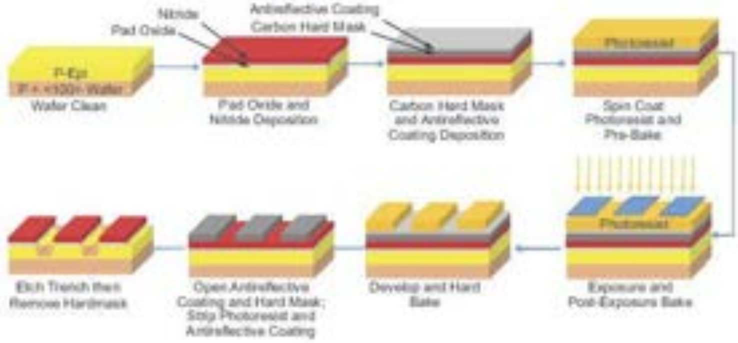
Chip inspection and metrology:

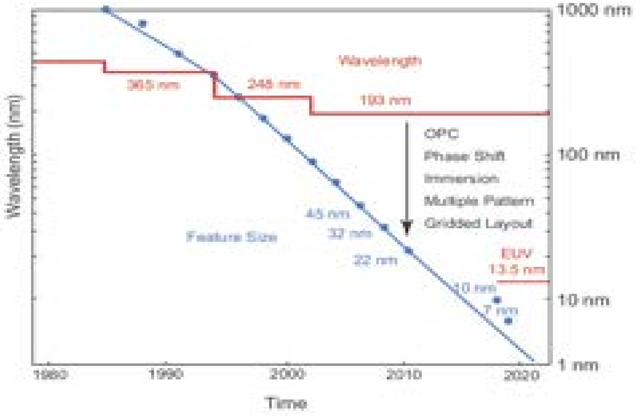
- Modern semiconductor technology is building vertically. Chips are now dozens of layers thick and planar metrology techniques (i.e. atomic force microscopes) are not capable of probing deep in the chip.
- New coherent diffraction imaging techniques using transverse coherence from synchrotron light are now capable of 3d imaging of chips with resolution of a few nm.

PHOTOLITHOGRAPHY IS A FUNDAMENTAL MANUFACTURING TECHNIQUE FOR CHIPS

Highly advanced nanofabrication techniques resulting from >60 years of development







The photon wavelength has decreased to produce smaller feature sizes. Modern systems use 13.5 EUV light for advanced chips.

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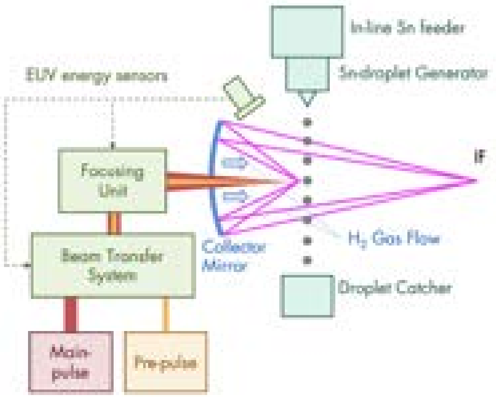
A VERY BRIEF REVIEW OF EUV LITHOGRAPHY

Laser Produced Plasma (LPP) is used as the EUV source.

Gigaphoton LPP-EUV Source System

Key Components

- **Sn-droplet Generator**
  - ✓ In-line Sn fuel system to extend lifetime with stable target supply
- **Main/Pre-pulse Laser**
  - ✓ High conversion efficiency without increased Sn plasma energy
- **Debris Mitigation**
  - ✓ Optimized H_2 gas flow and capping layer to extend mirror lifetime
- **Shooting Control**
  - ✓ High-accuracy spatial and temporal control between lasers and droplets to increase EUV energy stability



This source produces a few hundred W of EUV but has had a number of technical difficulties.

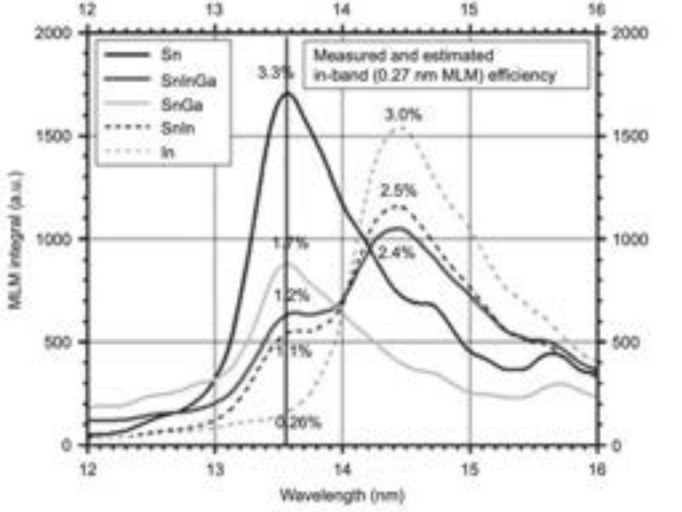
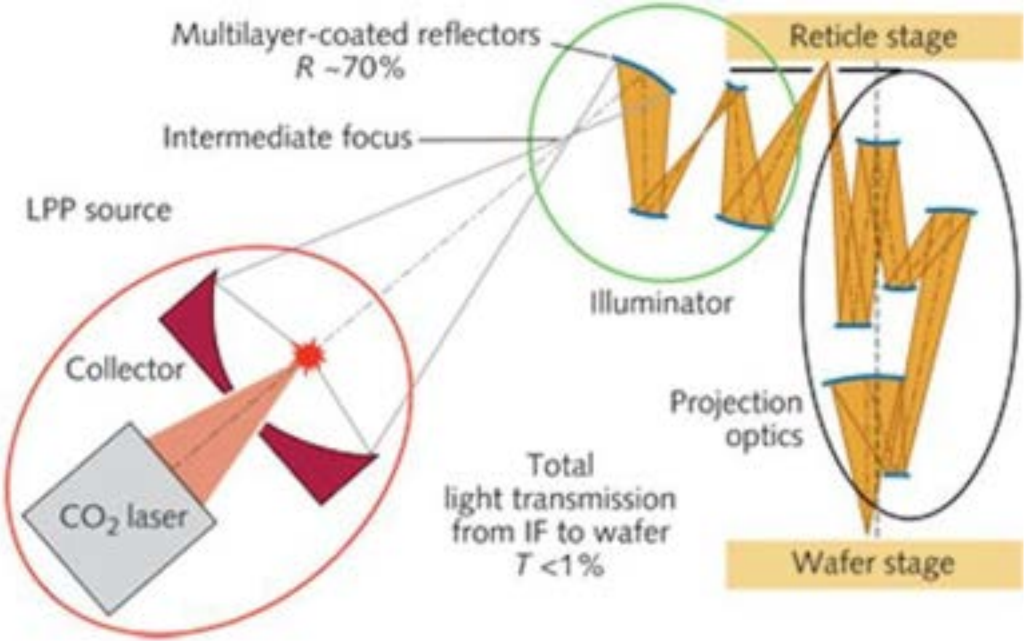


Figure 3 Measured conversion efficiency for a number of selected target materials.

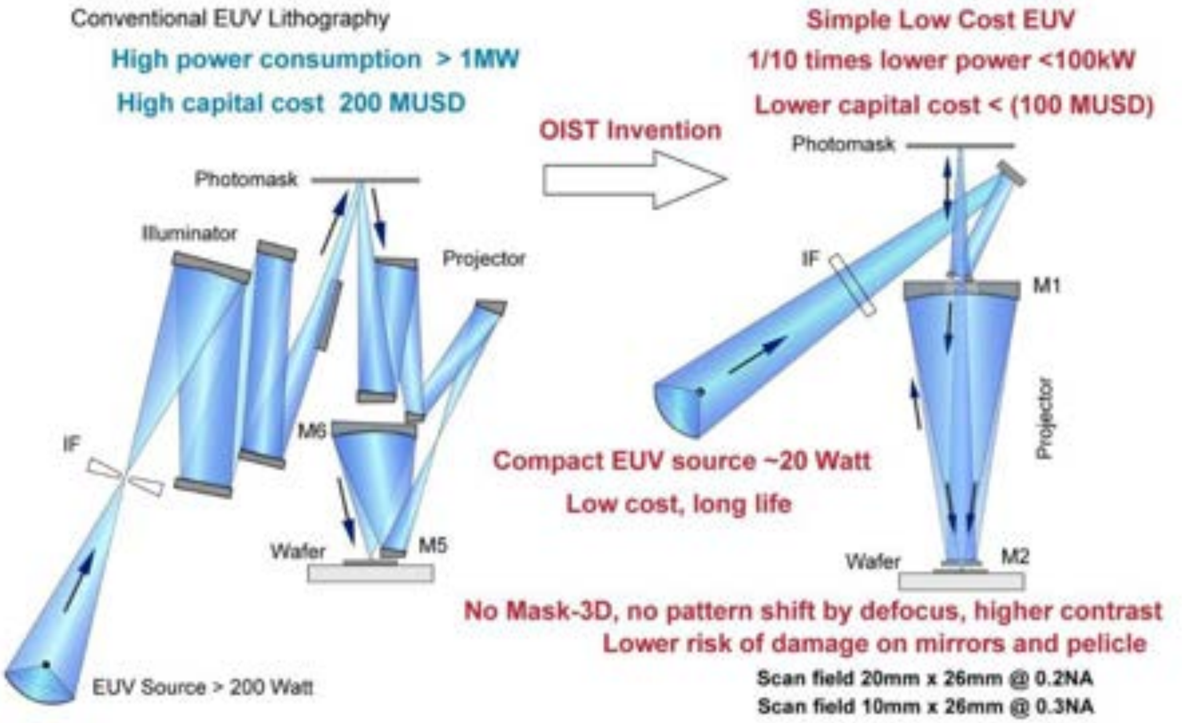
A VERY BRIEF REVIEW OF EUV LITHOGRAPHY
Illumination optics



A collector mirror focuses the light into a reflective optical system that directs the light onto a reticle, which a second set of mirrors, at right, focus onto the wafer stage. Reflection at each multilayer optic is ~75%. Overall transmission from the intermediate focus at top center to the wafer stage is less than 1%.

A PROPOSED SIMPLIFIED ILLUMINATION SCHEME

Proposed by Prof. Tsumoru Shintake (Okinawa IST) and well-known accelerator genius.



ASML IS THE WORLD LEADER IN EUV SCANNER TECHNOLOGY

HQed in Eindhoven, Netherlands

As of 2022, ASML has shipped around 140 EUV systems, and it is the only company to manufacture them. ASML's best-selling EUV product has been the TWINSCAN NXE:3600D, which costs up to $200 million. ASML's latest high-NA system, the EXE:5000, weighs 150 metric tons and has a comparable price tag of nearly $400 million.

THE SCALE OF MODERN CHIP FABS IS MUCH BIGGER THAN ALL ACCELERATOR FACILITIES

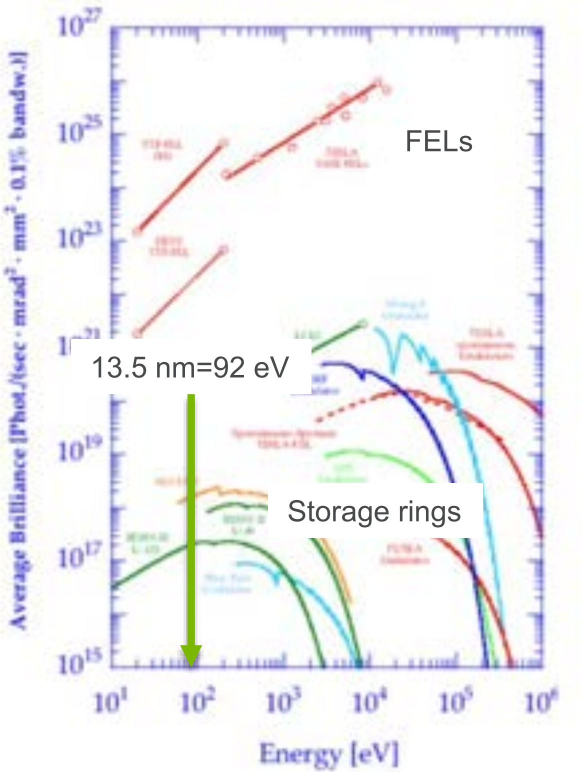
The cost of modern fabs far exceeds the cost of an accelerator and size can accommodate "compact" machines

- Cost of fab ~$40B
- Area of 2km x 2km
- Power installation of ~200MW

Photo of construction of new fab in Arizona and ideal view of final fab

CAN WE USE AN ACCELERATOR-BASED LIGHT SOURCE FOR EUV LITHOGRAPHY?

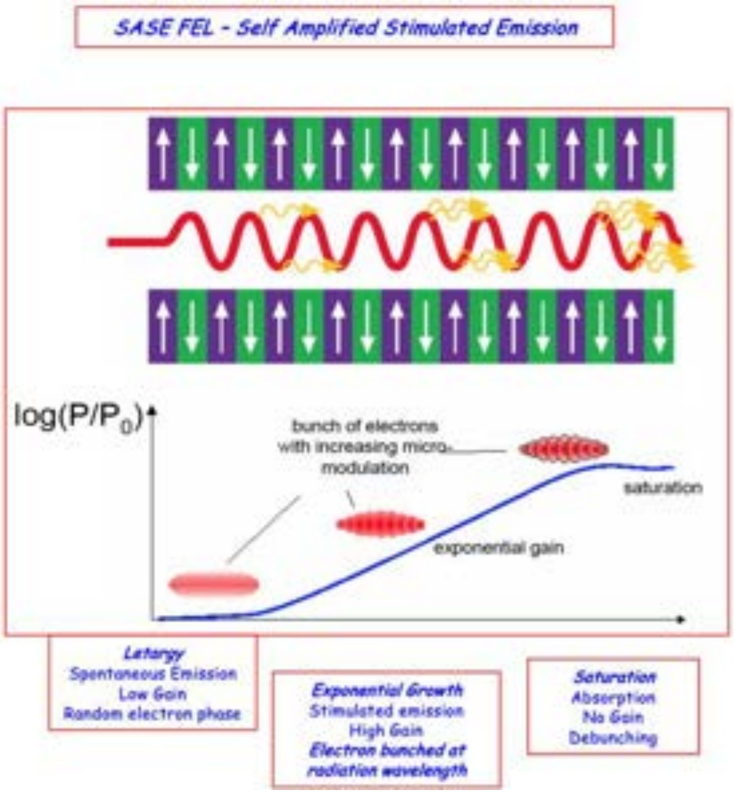
Light sources regularly provide light from IR to hard x-rays

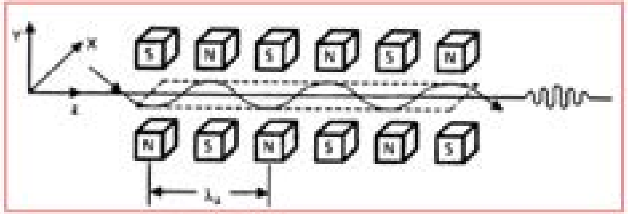


- Radiation from storage rings is high quality and transversely coherent for modern rings at 13.5 nm. Unfortunately, the maximum power is only a few watts.
- SASE FELS generate microbunching and produce several orders of magnitude increase in power. Many other FEL schemes can increase the beam power (laser seeding, RAFEL, etc.)
- Some schemes for microbunching in rings have been proposed.

LONGITUDINAL COHERENCE GREATLY ENHANCES OUTPUT POWER

An FEL “instability” microbunches beam and enhances power



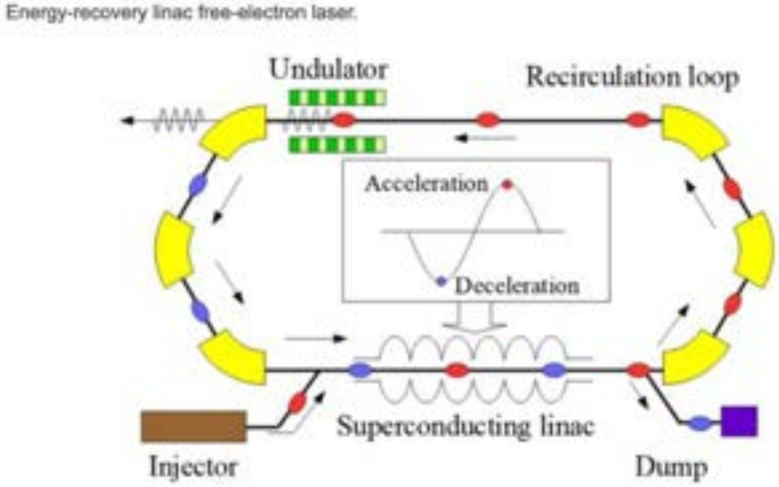


$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right) \approx \frac{\lambda_u}{2n\gamma^2}$$

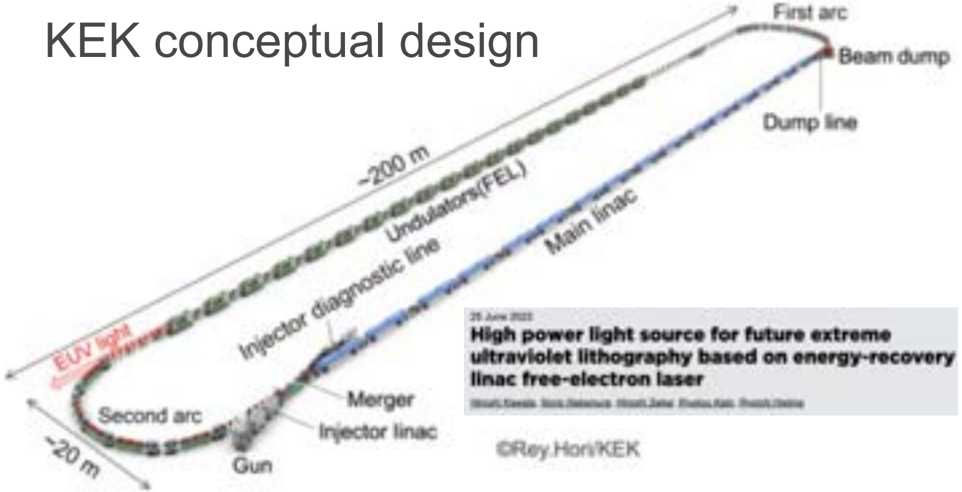
- For a 1 cm undulator period, K=1.41, a minimum beam energy of ~450 MeV is needed.

AN ENERGY RECOVERY LINAC IS AN ATTRACTIVE OPTION AS A HIGH POWER EUV SOURCE

Possible to lase at EUV wavelengths with energy efficiency



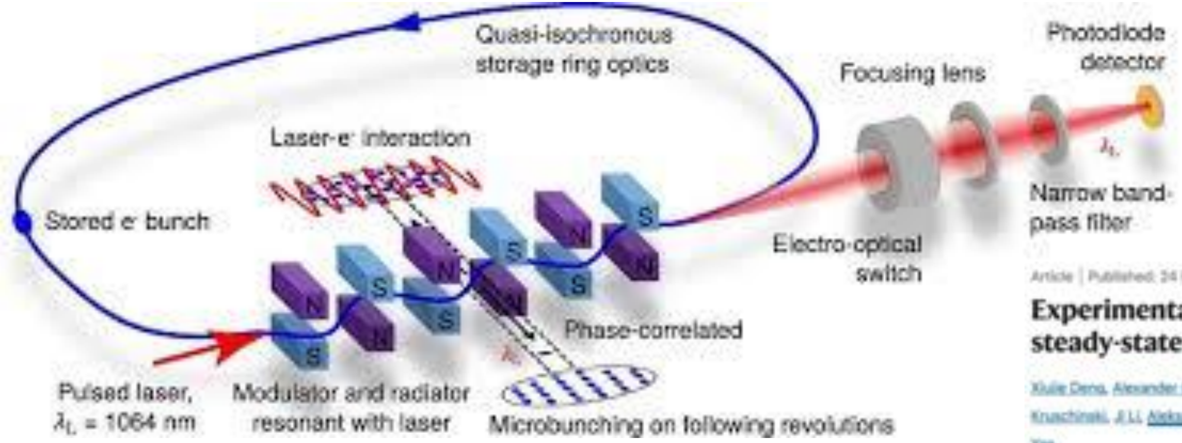
KEK conceptual design



- Several designs exist for ERL-based FELs to lase at 13.5 nm. Typical beam energy of 800 MeV and beam currents from 1-10 mA with power output at 10s of kW. This machine is not far beyond current state of the art. Several advantages of this including polarizability of light.
- Several labs and companies are trying to make this a reality.

STORAGE RING MICROBUNCHING IS ANOTHER INTERESTING APPROACH

Still in early stages with many things to be demonstrated



Article | Published: 24 February 2021

Experimental demonstration of the mechanism of steady-state microbunching

Xiujie Deng, Alexander Chao, Jörg Feikes, Arne Hoehl, Wenhui Huang, Roman Klein, Arnold Kruschinski, Ji Li, Aleksandr Matveenko, Yuriy Petenev, Markus Ries, Chuanxiang Tang & Lixin Yan

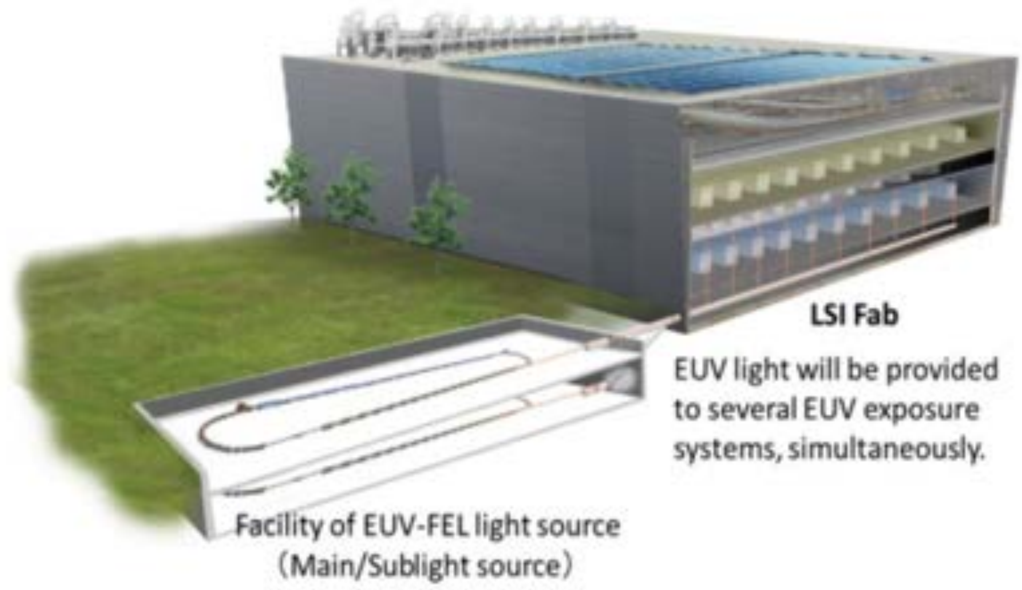
Nature **590**, 576–579 (2021) | Cite this article

- A laser is used to microbunch the beam and coherently produce EUV light. In some schemes (SSMB), the lattice allows the microbunching to remain for multiple passes.

HOW DO WE INTEGRATE ACCELERATORS IN A FAB

Any new capability has to integrate with a large production facility

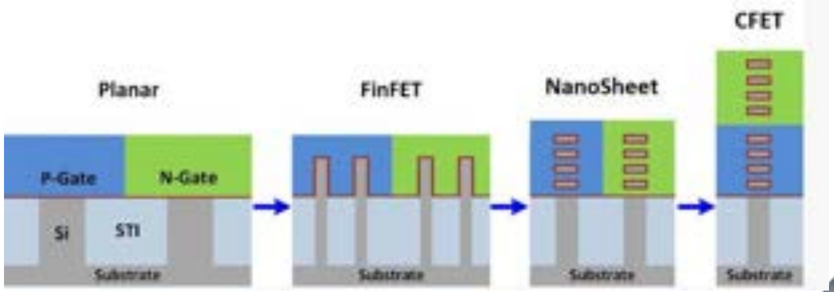
Schematic view of the LSI Fab based on the EUV-FEL light source. FEL light is distributed into 10 scanner systems using a guide beamline.

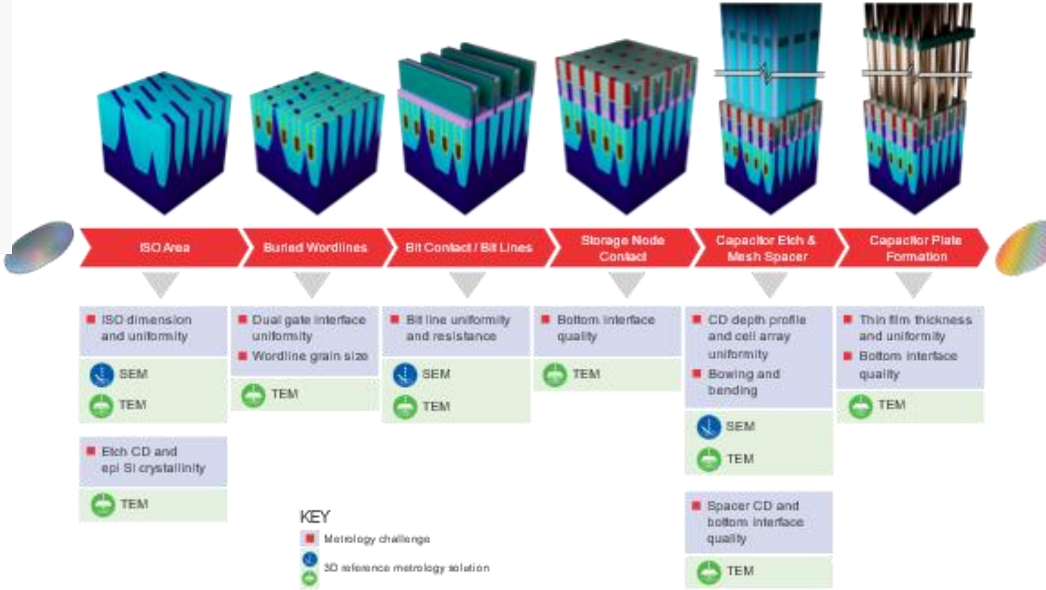


- Safety-radiation shielding
- Large cryogenic system needed.
- Very High Reliability (>99%). Possible option is to build two.
- Easy operation requiring minimal staff with remote control.
- Must be cost-effective to stay viable.

CHIP INSPECTION AND METROLOGY

A broad set of metrology tools are used for 2D inspection. With modern chips building upwards, a 3D inspection tool is needed.

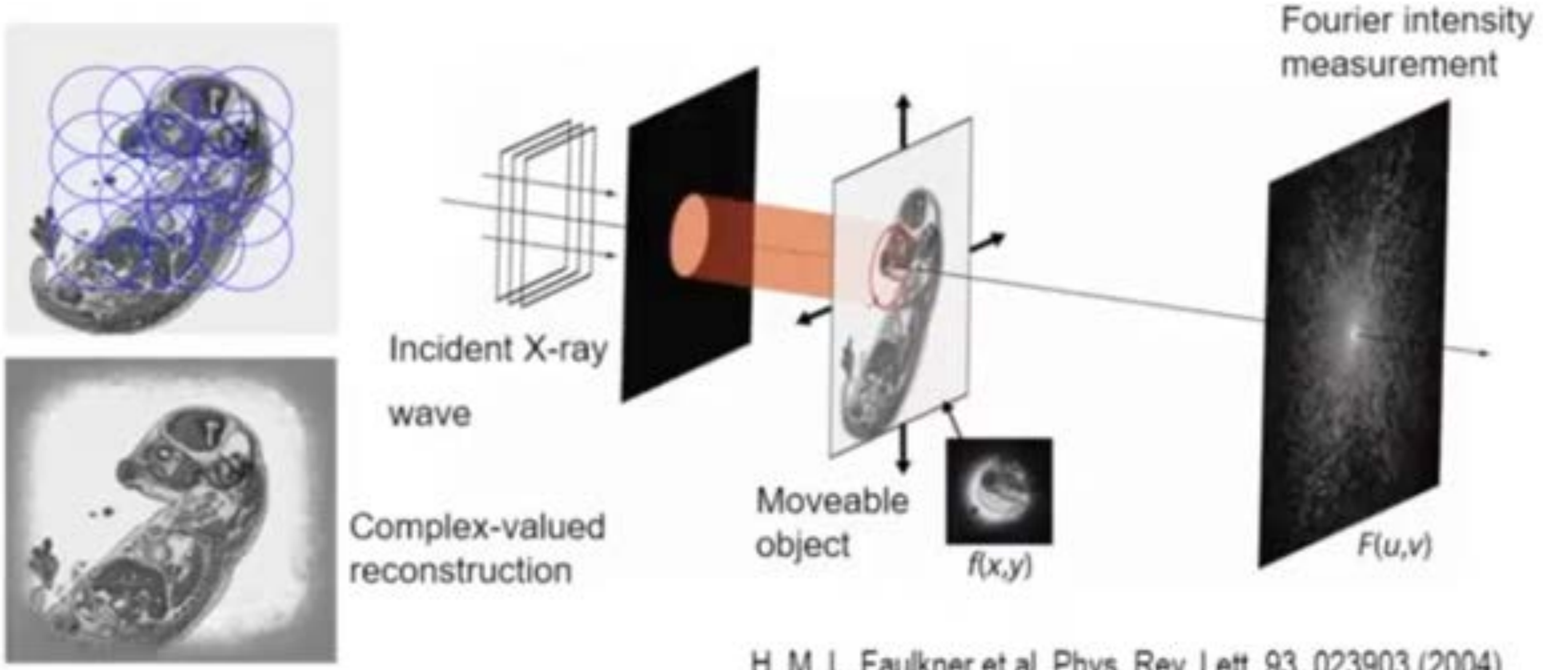




- Modern techniques are adding multiple layers to chips.
- Electron microscopy (STEM, etc) provides atomic resolution but does not extend deep into the chip.
- How can the accelerator community help with this?

A NEW TECHNIQUE FOR HIGH RESOLUTION 3-D MAPPING OF OBJECTS

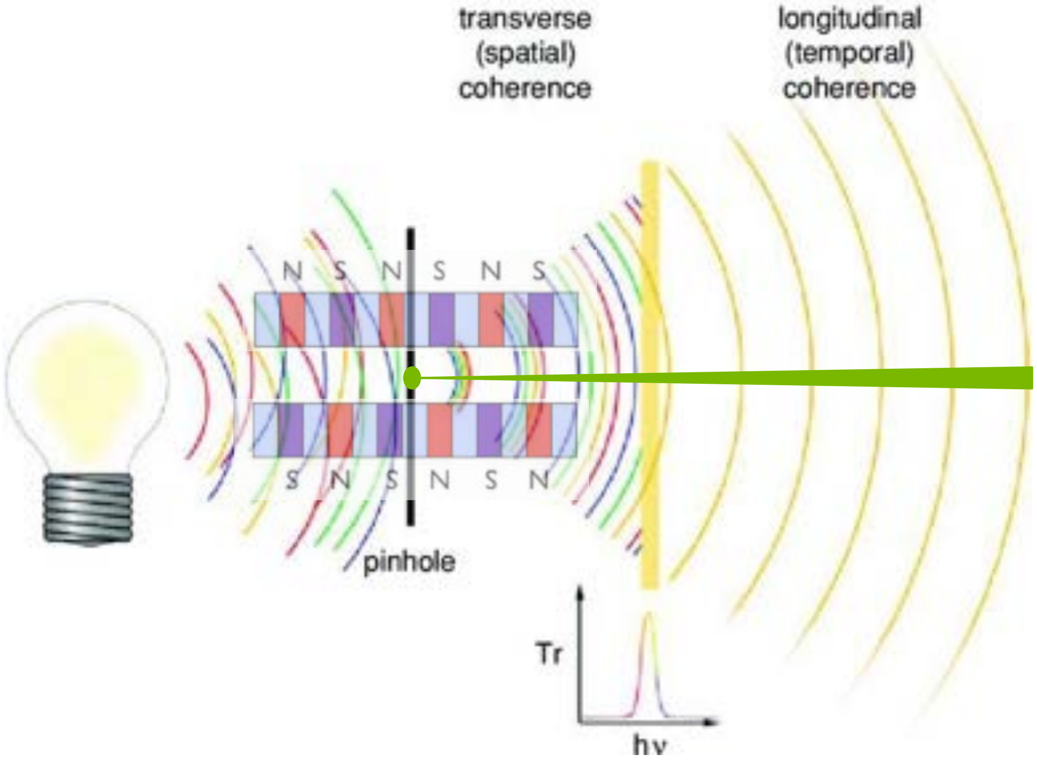
Laminar ptychography uses lensless coherent diffractive x-ray imaging to reconstruct 3-D objects such as microelectronics



H. M. L. Faulkner et al. Phys. Rev. Lett. 93, 023903 (2004)

QUICK ASIDE: COHERENCE OF SYNCHROTRON RADIATION

Small electron beams make effective slits for transverse coherence



- Slits can make any light source transversely coherent but with significant loss in flux.
- Bandpass filters add longitudinal coherence but with more loss in flux.
- The ultralow emittance electron beam acts as a slit where all photon wavelengths larger than the emittance are coherent.
- The undulator then acts as a bandpass filter with no loss providing a narrow linewidth.

THE HOLY GRAIL IS A DIFFRACTION LIMITED X-RAY SOURCE

This has been the dream since the origin of synchrotron light

$$\frac{\lambda}{4\pi}$$

$\lambda = 1\text{Å} \Rightarrow \varepsilon_{diff} = 8$ pm-rad

- The minimum photon spot size is reached at the diffraction limit.
- The production of large fluxes of coherent light at Angstrom wavelengths is expected to open whole new areas of x-ray sciences.
- N.B. The physics of X-ray FELs requires the geometric electron emittance to meet this criterion to achieve lasing and thus is transversely coherent by definition.

NANOSCALE 3D IMAGING

Combining ptychography and a sample rotation enables 3D imaging

Laminography geometry allows for extended flat samples to be imaged, enabling 3D zooming into regions of interest and facilitating in situ and in operando studies

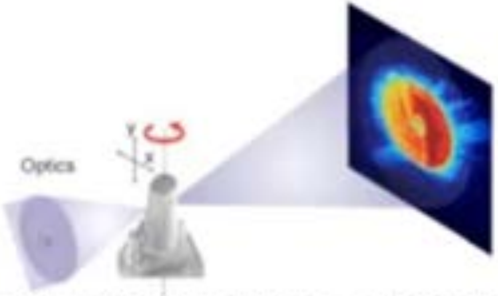
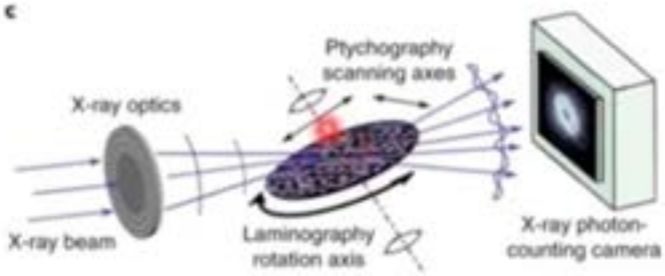


Image modified from Donnelly *et al.* Nature 547, 328 (2017)

Ptychographic X-ray computed tomography (PXCT)

Dierolf *et al.* "Ptychographic X-ray computed tomography at the nanoscale," Nature, **467** 436 (2010)

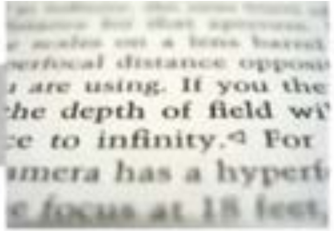


Ptychographic X-ray laminography (PyXL)

Holler *et al.*, "Three-dimensional imaging of integrated circuits with macro- to nanoscale zoom," Nat. Electron. **2**, 464 (2019)

COMPUTATIONAL IMAGING TECHNIQUES CAN RESOLVE DEPTH OF FIELD LIMITS

Diffraction effects of other layers are included in reconstruction of an individual slice



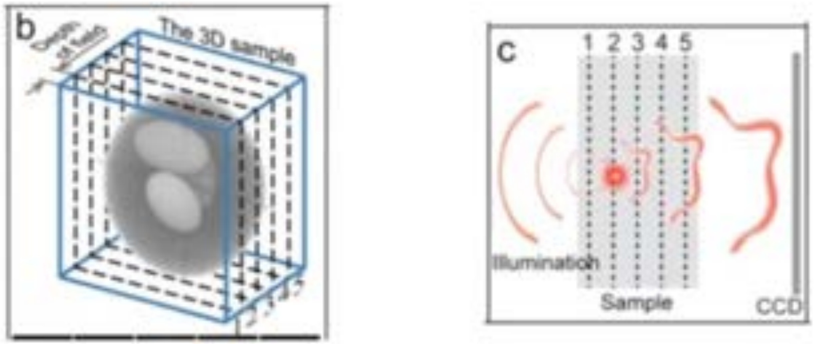
https://commons.wikimedia.org/wiki/File:DOF-ShallowDepthofField.jpg

Depth of field (DOF) arises due to diffraction. Affects lens-based imaging, holography, etc.

Higher resolution results in smaller distance remaining in focus. Limiting the volumes we can measure with very high resolution.

Multislice ptychography overcomes this limitation. Represents the object by several slices and taking into account propagation through the object.

Maiden *et al.*, "Ptychographic transmission microscopy in three dimensions using a multi-slice approach," JOSA A **29**, 1606 (2012). https://doi.org/10.1364/JOSAA.29.001606



Images from Li & Maiden, Sci. Rep. 8, 2049 (2018). Under Creative Commons Attribution 4.0 International License.

EXAMPLES OF CURRENT RESULTS

Results of measurements from Holler, et al. done at the Swiss Light Source

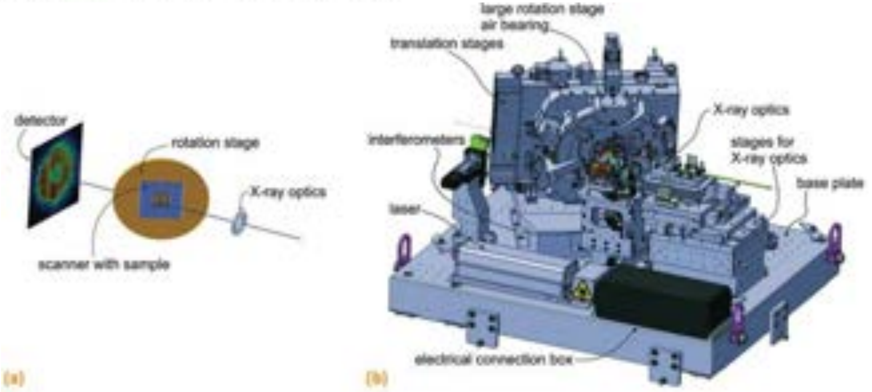
ARTICLES

https://doi.org/10.1038/s41928-019-0309-z

nature electronics

Three-dimensional imaging of integrated circuits with macro- to nanoscale zoom

Mirko Holler[1*], Michal Odstrcil[1], Manuel Guizar-Sicairos[1], Maxime Lebugle[1], Elisabeth Müller[1], Simone Finizio[1], Gemma Tinti[1], Christian David[1], Joshua Zusman[2], Walter Unglaub[2], Oliver Bunk[1], Jörg Raabe[1], A. F. J. Levi[2] and Gabriel Aeppli[1,3,4]



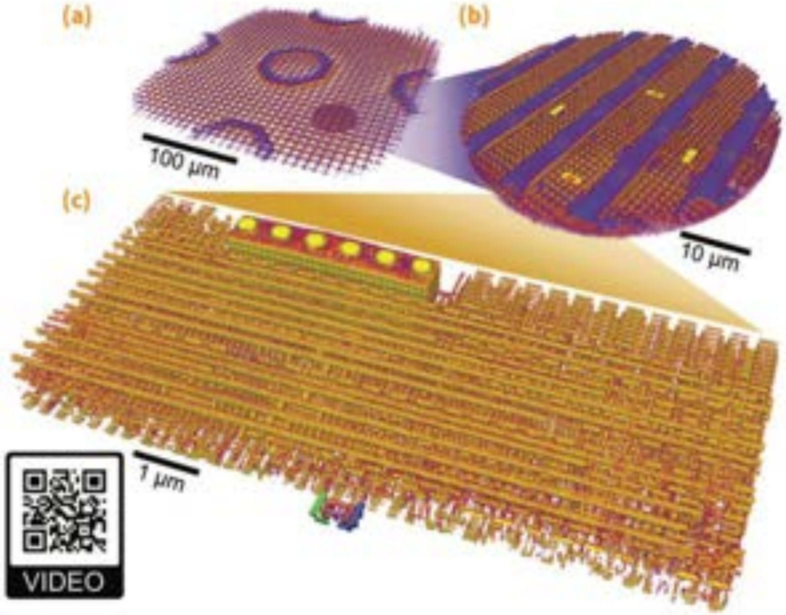
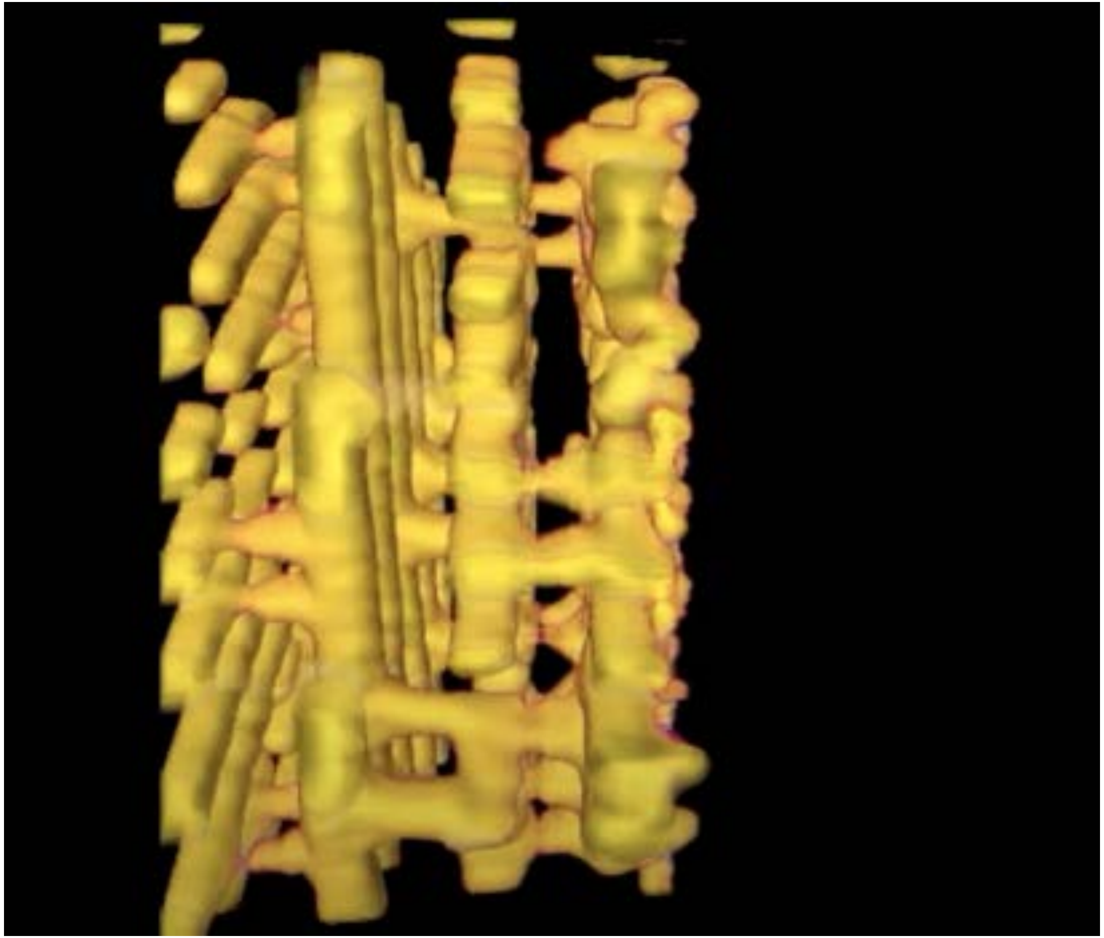
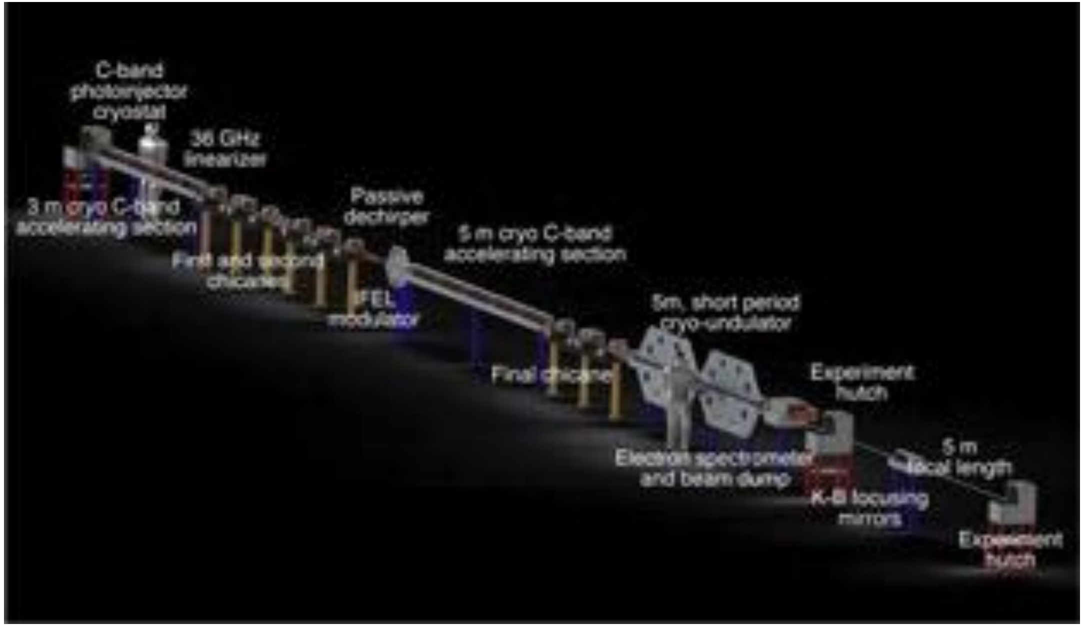


Fig. 5 3D rendering of the laminography measurement dataset. (a) A combined rendering of the low resolution and high resolution dataset. (b) A rendering of only the volume measured at high resolution. (c) A rendering of a sub-volume of (b). In front of this region a functional unit of the circuit is color coded. Figure adapted from Holler et al.[28]



THE UCXEL: AN EXAMPLE OF A COMPACT LINAC-BASED XFEL

A XFEL design led by Jamie Rosenzweig that reoptimizes for compactness using the latest accelerator technologies.



Schematic of ~1 Gev scale compact XFEL

instruments MDPI

Article

A High-Flux Compact X-ray Free-Electron Laser for Next-Generation Chip Metrology Needs

The concept for a compact XFEL for chip metrology scales the UCXFEL concept to ~2.5 GeV:

-high gradient cryo C-band RF

-high brightness injector

-short period undulator

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X-RAY FEL NUMEROLOGY: INSTABILITY AND GAIN

- X-ray FEL has numerous input parameters. Recap:
- Gain parameter (1D)

  MAXIMIZE $\rho^3 \simeq \frac{I}{4I_A}\frac{\gamma K_u^2}{k_r^2 \sigma_x^2}$

- Gain length $\boxed{L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}}$
- Efficiency $\eta = N_\gamma \hbar\omega_r / N_{e-}U \approx \rho$
- Coherence $\varepsilon_n < \lambda_r \gamma / 4\pi$

(Pellegrini criterion)

- Energy spread $\sigma_\gamma / \gamma \cup \rho$
  - Avoid Landau damping
- Focusing strength $\beta_x \cup L_g$

(e-beam “Rayleigh range”)

Merged analysis for optimizing XFEL. Maximize:

MAXIMIZE $$\rho \approx \frac{\gamma^6}{3}\left(\frac{\lambda_r}{2\pi}\right)^4 B_{6D}$$

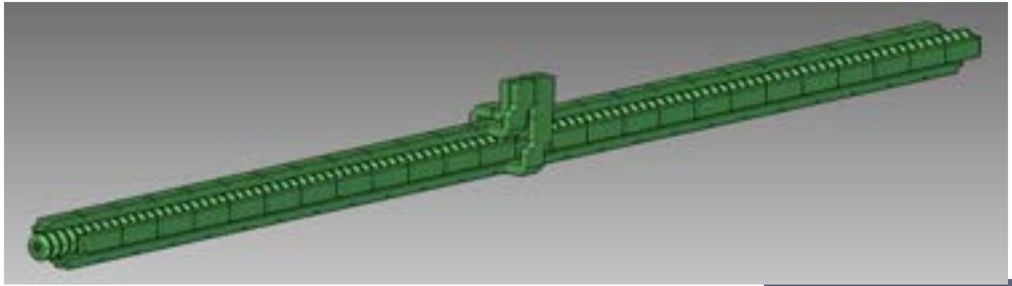
with the **6D electron beam brightness** def’n:

$$B_{6D} = \frac{2I(A)}{\sigma_\gamma \varepsilon_n^2}$$

Low γ implies large B_{6D}

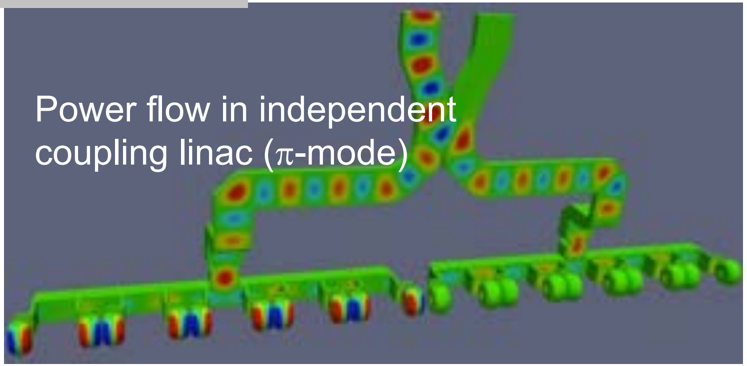
HIGH GRADIENT CRYOGENIC RF LINAC

- Design is for **125 MeV/m** gradient in novel cryo-linac (as in C^3)
  - New independent coupling through manifold developed at SLAC
- **Only 8 meters to reach 1 GeV**
  - Instabilities (LSE, CSR) have little time to develop



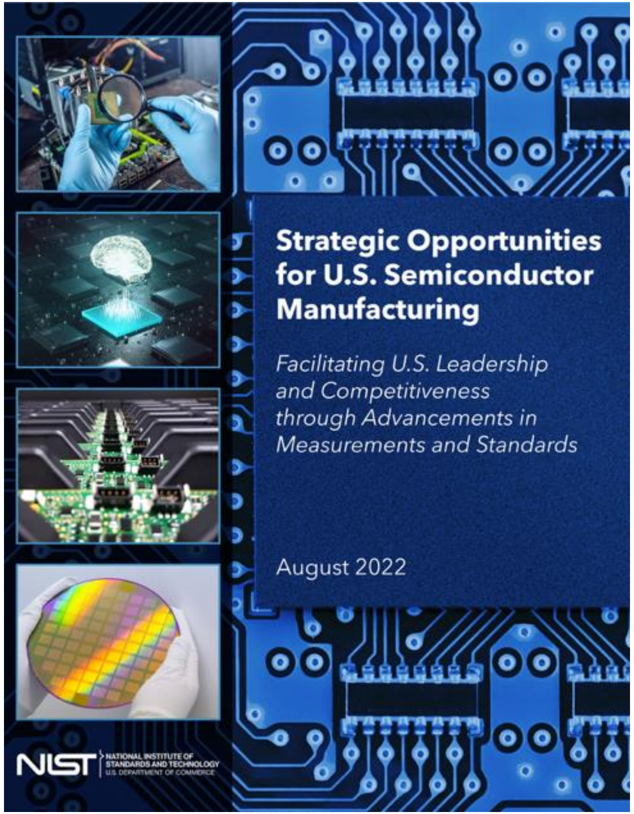
RF structure rendering (135 degree phase advance optimization, from S. Tantawi

- Original linac (right) is baseline for C^3 project
- *Photoinjector can produce collider quality flat beams*



METROLOGY IS EXPLICITLY CALLED OUT IN US REPORT (CHIPS ACT)

“**The measurement challenges impacting the U.S. semiconductor industry are at a critical stage and must be addressed** if we are to ensure U.S. leadership in this important sector,” said Under Secretary of Commerce for Standards and Technology and NIST Director Laurie E. Locascio. “We’ve received extensive feedback from stakeholders across industry, academia and government that will help us provide urgently needed measurement services, standards, manufacturing methods and test beds and build even stronger partnerships with this industry.”



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SUMMARY

- The microelectronics industry is one of the most dynamic in the technology sector and has a huge impact on our society.
- .However, as of today, particle accelerators have not had a huge impact on this field.
- New developments in accelerator science, technology and engineering are opening new ways for our field to contribute to this industry.
- We will see if any of these new ideas are adopted over the next decade or so.