TESSA – introduction, applications and road map

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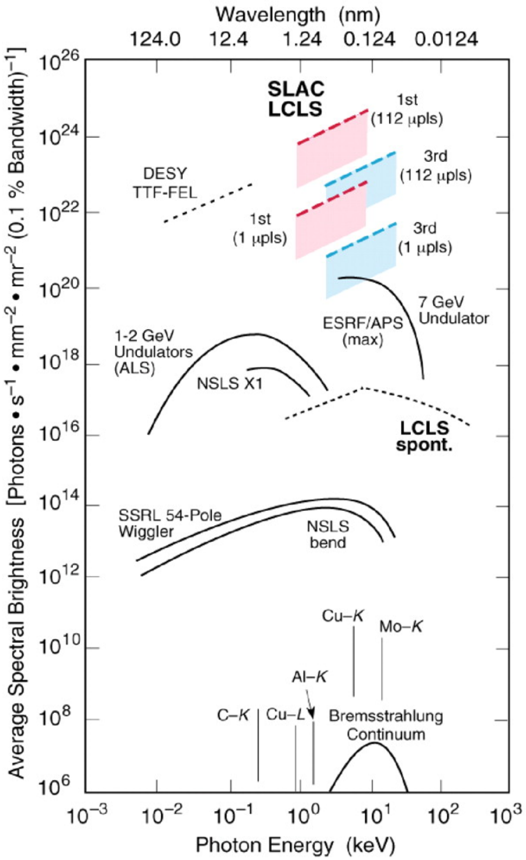
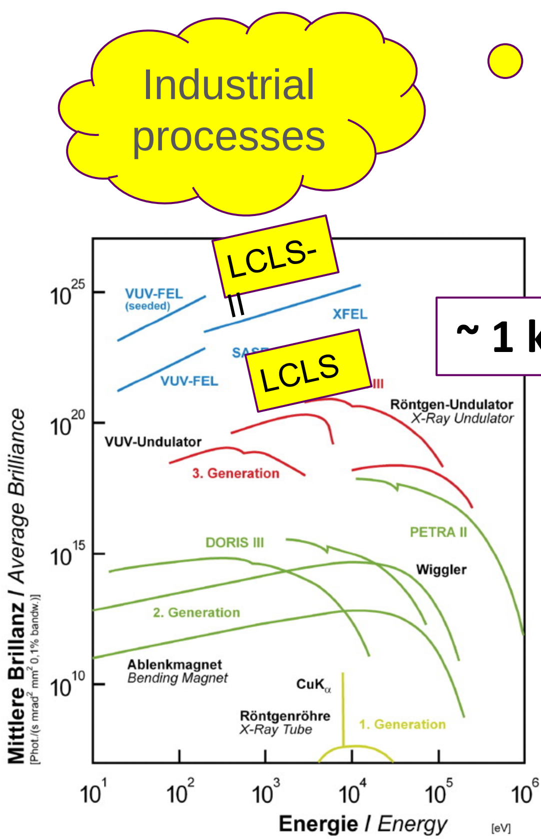
X-FEL for industrial processes

- X-ray FELs are established as research tools
- Can X-FEL become manufacturing/industrial tools?





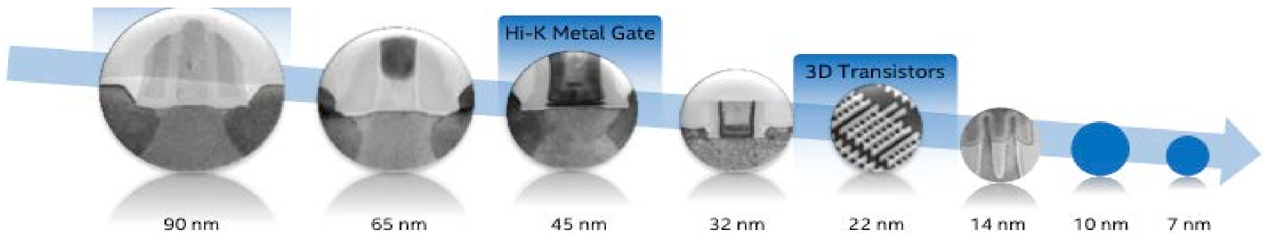
~ 100,000 kW-hr/year

> 2,000 kW-hr/year

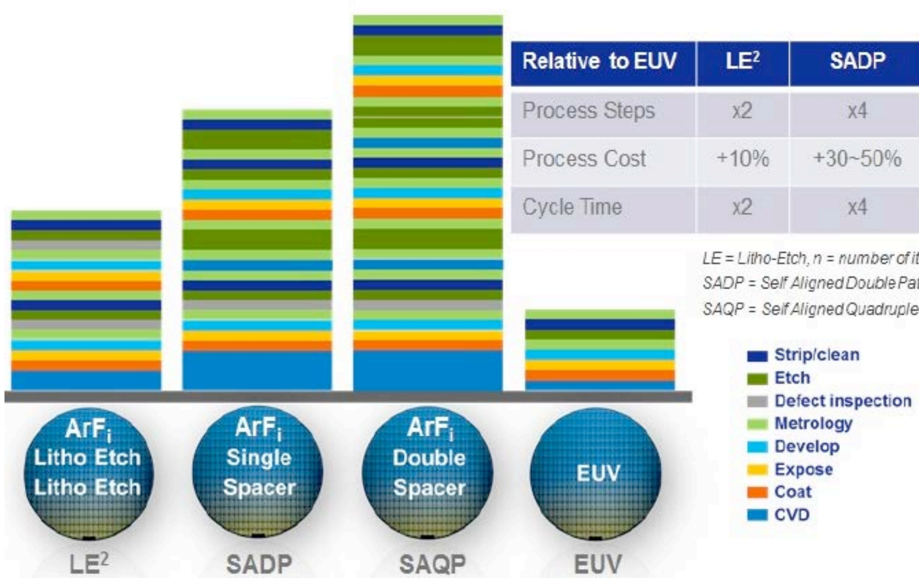
~ 1 kW-hr/year

Need to reduce cost per photon by >2 orders of magnitude compare to LCLS-II

Semiconductor industry roadmap



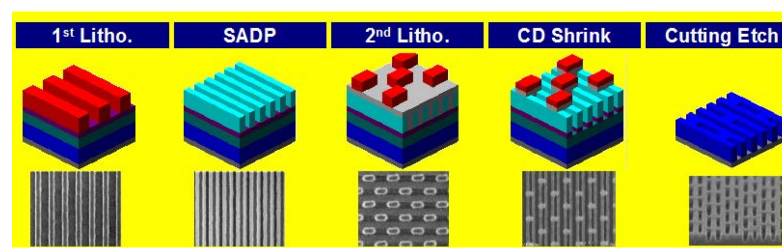
LE 248 nm	LE → immersion → LE² → SADP → SAQP 193 nm laser	LE 13.5 nm



Relative to EUV	LE²	SADP	SAQP
Process Steps	x2	x4	x5
Process Cost	+10%	+30~50%	+>50%
Cycle Time	x2	x4	x5

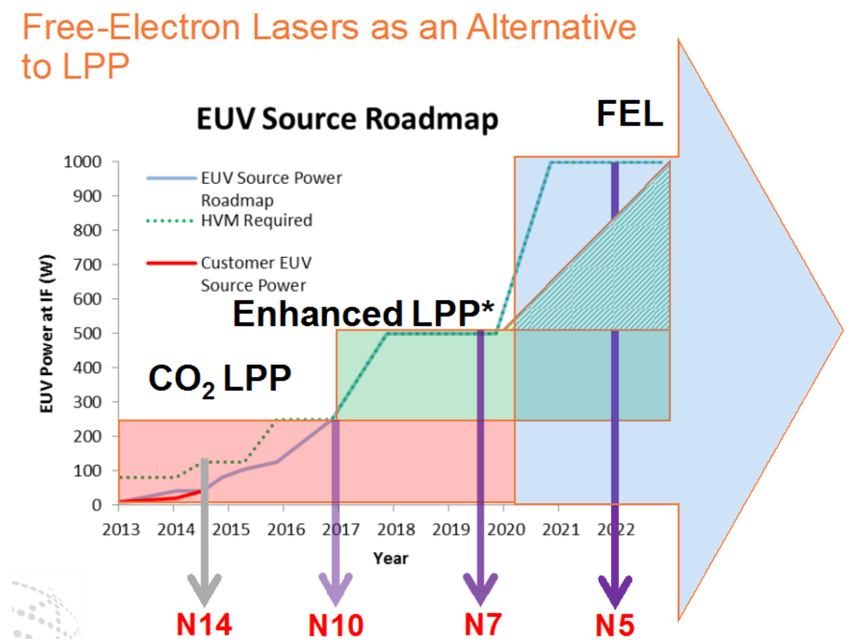
LE = Litho-Etch, n = number of iterations
SADP = Self Aligned Double Patterning
SAQP = Self Aligned Quadruple Patterning

- **Multi-patterning is too expensive to maintain Moore's law past n10**
- **EUV lithography can fill the gap**



EUVL source challenge

- EUV lithography @ 13.5 nm is the most economic solution beyond N10
- Power per scanner: 250 W for insertion, 1 kW at full capacity
- LPP limiting factors: debris mitigation, heat management, CW CO2 lasers
- It is expected that LPP will reach 250 W, but not kW
- LPP are expensive: ~ $70 M each
- FEL can offer non-granular solution (10-30 kW CW FEL to power the entire foundry)

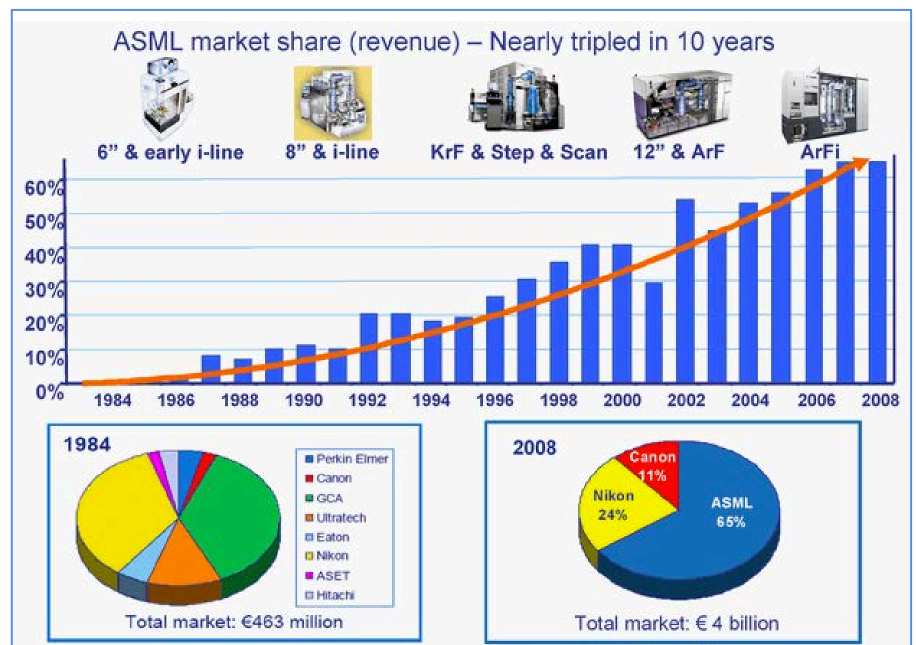


E. R. Hosler *et al* "Considerations for a free-electron laser-based extreme-ultraviolet lithography program", Proc. of SPIE **9422**, 94220D-1 (2015).

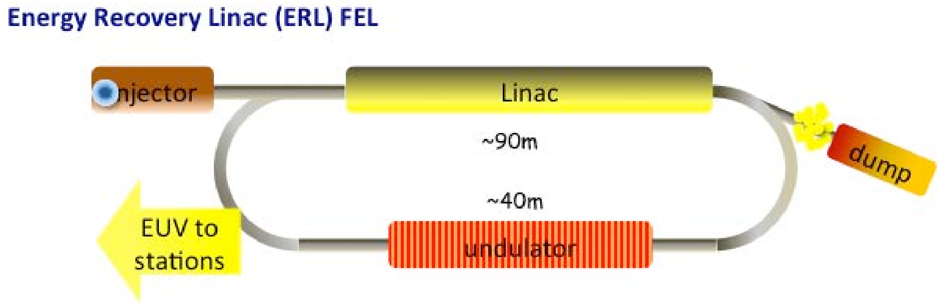
Industry consolidation

- A cost of modern HVM fab facility ~ $10 billion
- 4 companies consolidated most of the high end market
- 1 company (ASML) dominates tools market
- Presumably in 2012 ASML initiated internal EUV FEL R&D program (presently on hold)

ASML is at the center of the industry ecosystem for over a decade



10 kW class FEL topology options and risks



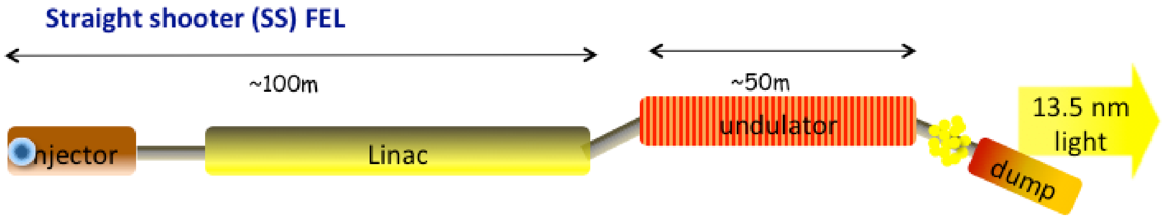
Leveraged on Jlab design and 10 kW IR ERL FEL

Closed system, has to be developed and tested in its entirety

High injected/recirculated current, machine protection is an issue

Untested physics of short wavelength ERL FEL

Very elegant solution to reducing the RF power and beam dump costs



Can be leveraged on LCLS-II design and development

Extensive practical experience with single pass X-FEL, large pool of experts and trained personnel

Well developed modeling tools

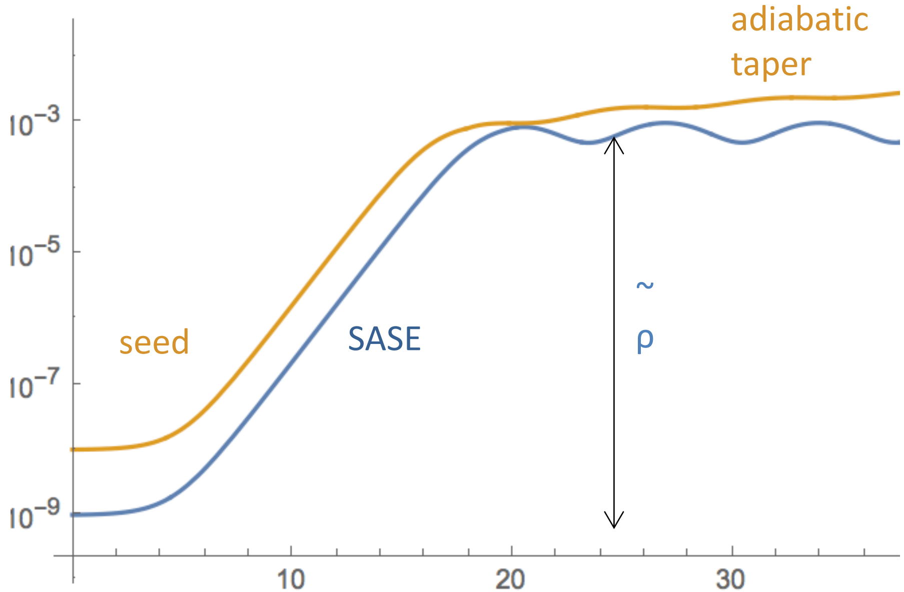
Untested physics of high efficiency short wavelength FEL

Modular design, enables future upgrades, also testing can be done in existing facilities

(pictures courtesy of J. Byrd, LBNL)

FEL efficiency

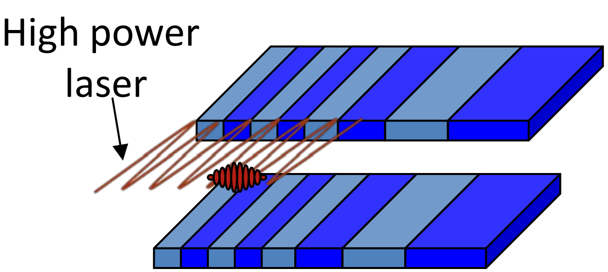
- SASE efficiency is limited to Pierce parameter (~ 0.1% at EUV)
- Conventional adiabatic tapering: keep the bunched beam in phase and let it radiate; efficiency per length is usually about the same (~ 1 MeV/m for EUV)
- Conventional tapered FEL efficiency is limited by de-bunching, sidebands, and practical undulator length



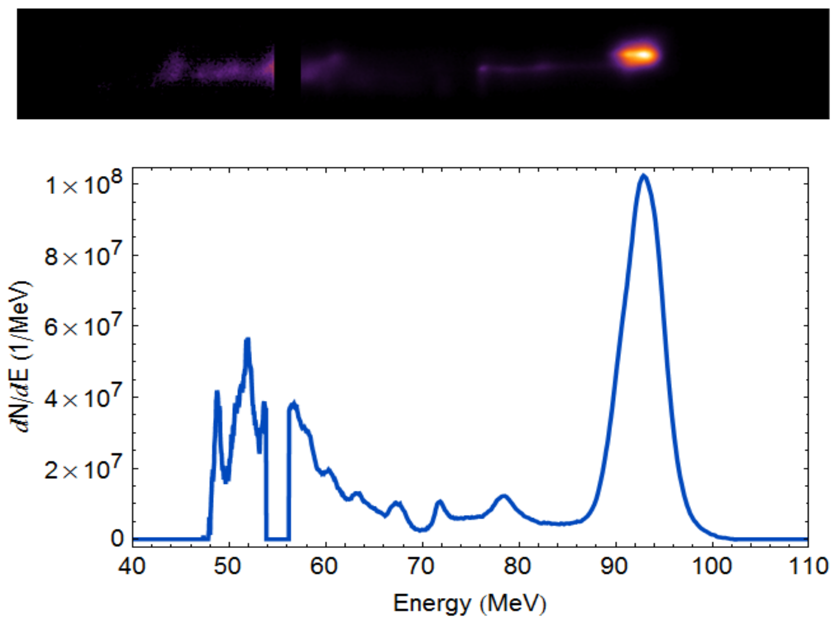
IFEL experience

- IFEL demonstrated energy exchange rate ~ 100 MeV/m
- Strong seed + strong tapering = high gradient
- ***There is no media losses, the process should be reversible***
- ***IFEL in reverse = TESSA***

(**T**apering **E**nhanced **S**timulated **S**uperradiant **A**mplification)



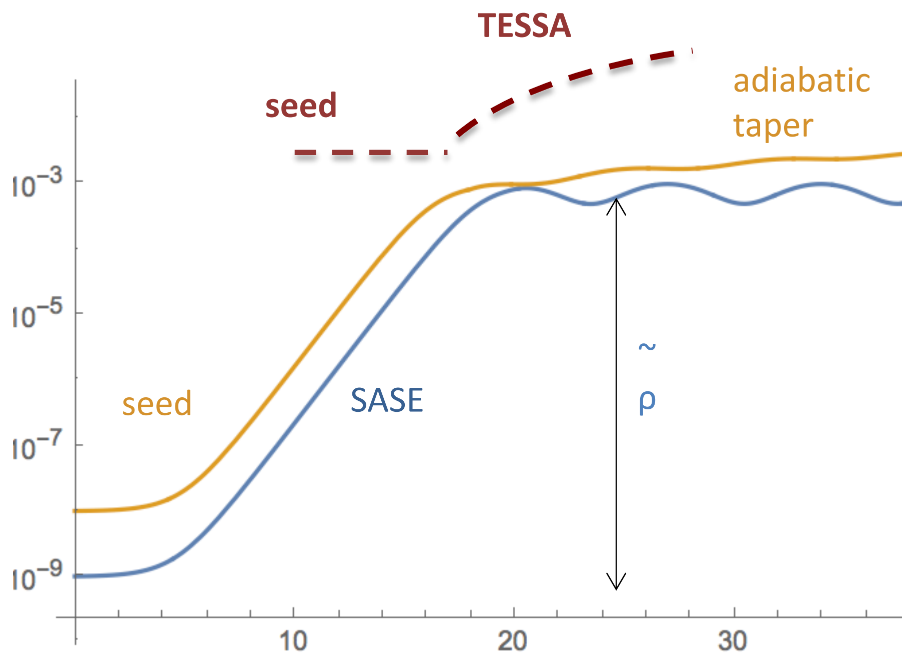
In an IFEL the electron beam absorbs energy from a radiation field.



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

TESSA vs. Tapered FEL

- Large seed intensity (above SASE saturation intensity)
- Fast deceleration through stimulated emission (> 10 MeV/m)
- Strong taper (period by period optimization)
- Possibility of >50% efficiency in a relatively short interaction distance



TESSA roadmap

- Applications are at EUV (possibly THz), and also at very high powers (> MW)
- 10 µm TESSA decelerator successful (UCLA experiments, 2015-2016), UCLA program is ongoing
- Next steps (2017-2019):
  - Demonstration of TESSA amplifier (lower seed energy)
  - Experimental study of wavelength scaling

  [can be done at LEA beamline, topic of this workshop]
- Beyond the next steps:
  - Short wavelengths (no seeds and poor mirrors)
  - TESSA oscillator
  - Integration with superconducting RF

  [migration to Fermilab]