High efficiency 10 kW class FEL for EUV lithography

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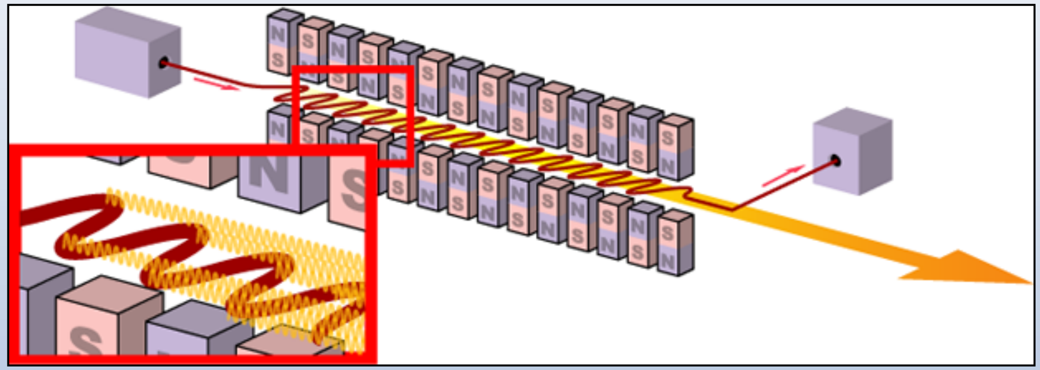
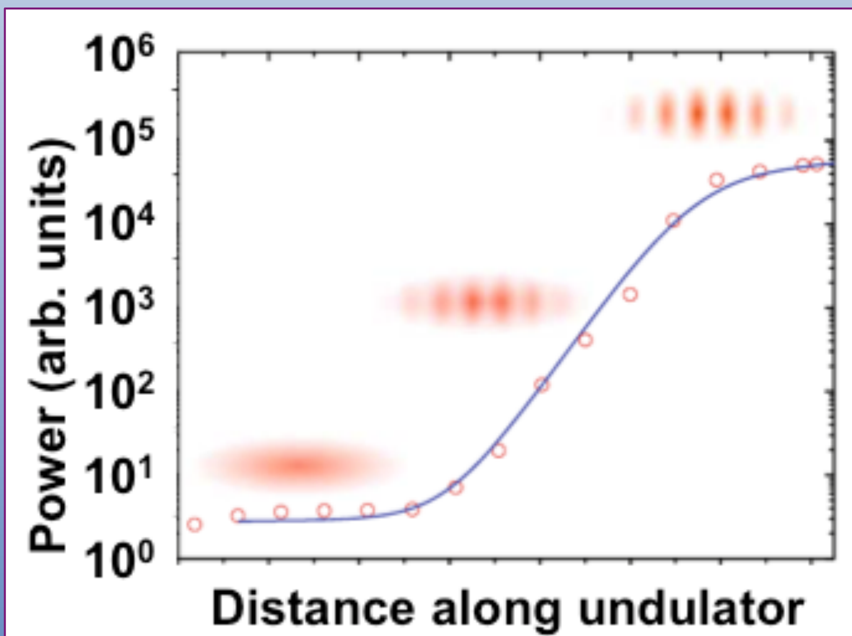
Outline

- The case for industrial EUV FEL
- US EUV FEL consortium
- CW EUV FEL based on existing components
- Summary

From lamps to lasers

- XFEL – like an introduction of optical lasers – is a paradigm shift in X-ray technology





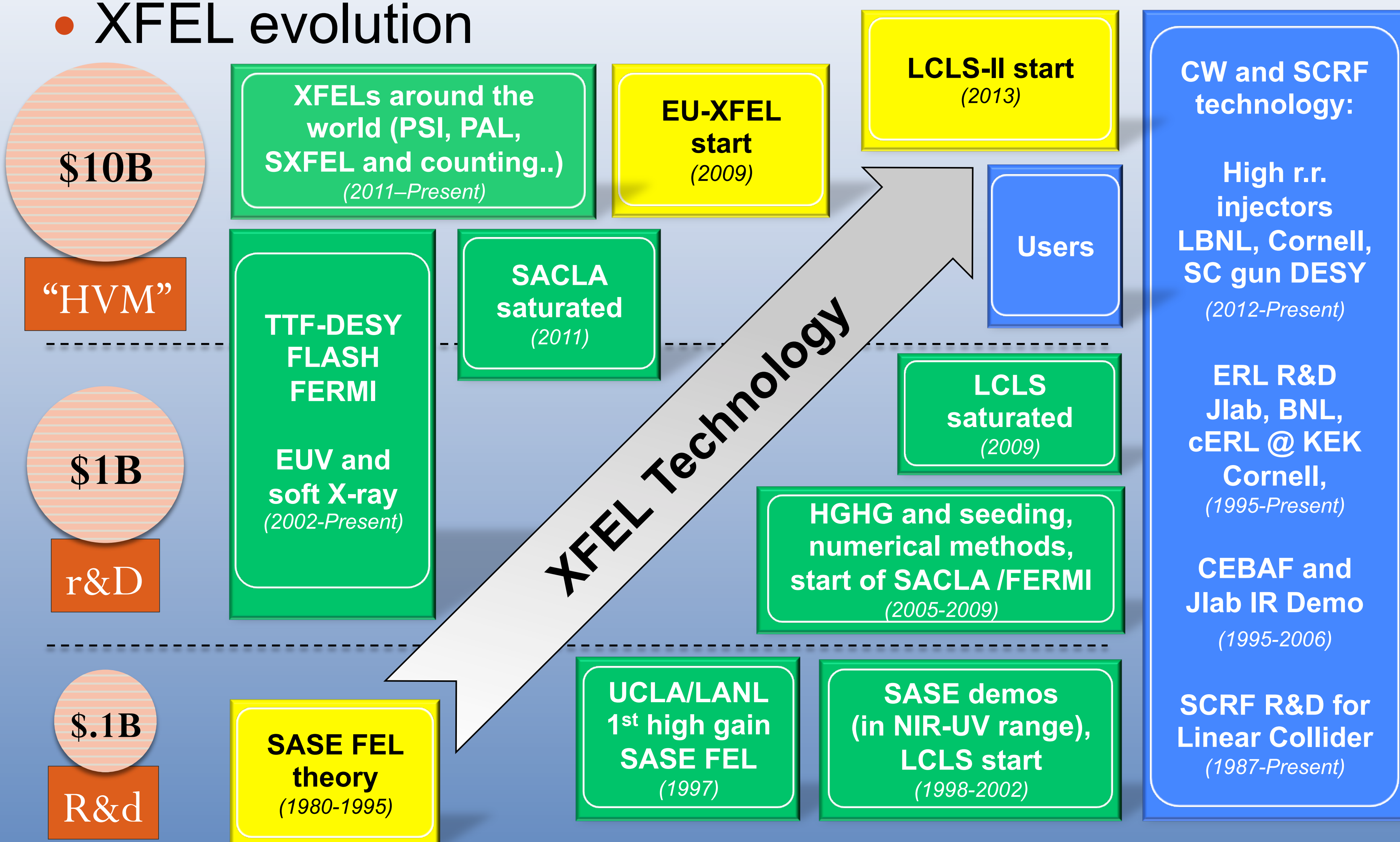
Coherent Synchrotron Radiation (XFEL)
10^4-10^6 in-bandwidth photons per electron

SASE FEL

Incoherent Synchrotron Radiation
0.01-1 in-bandwidth photons per electron

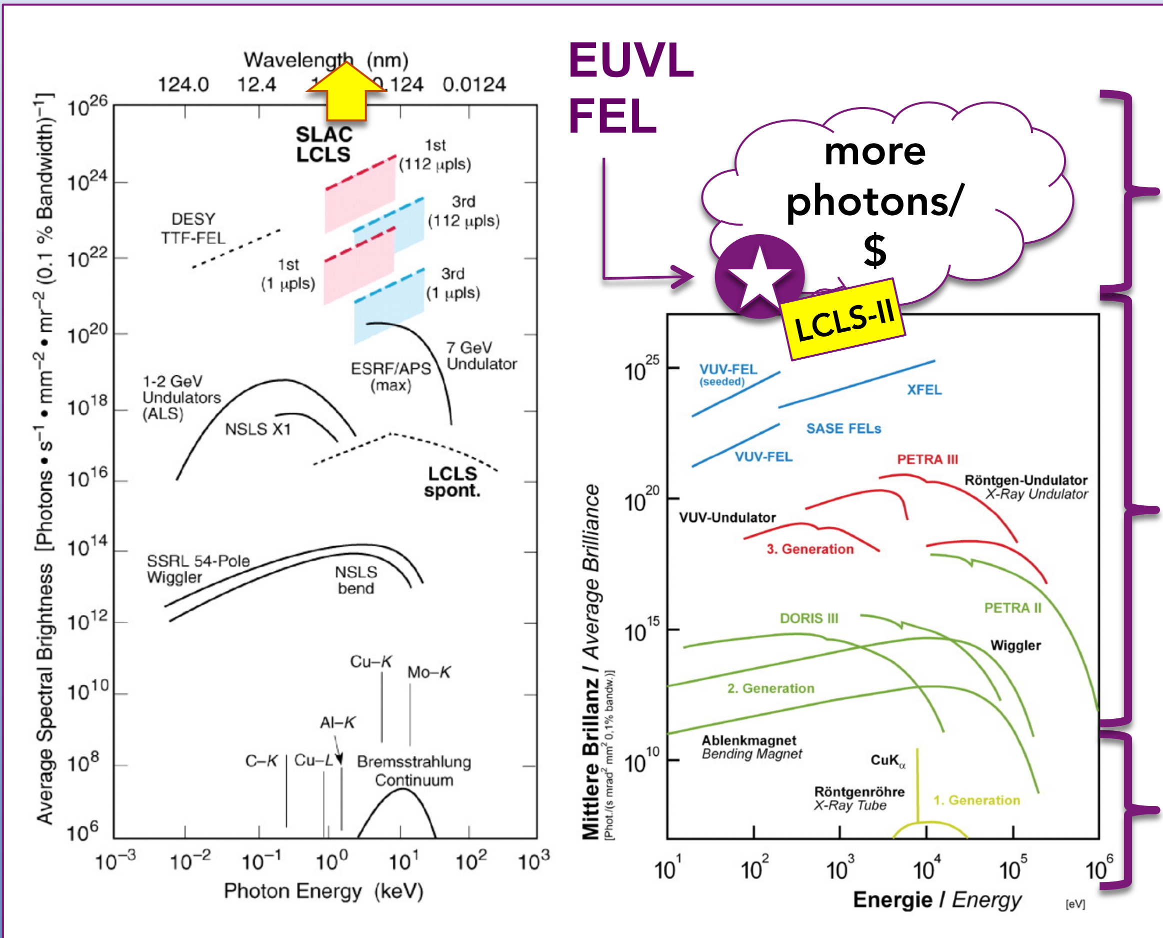
Form idea to users facility

- XFEL evolution



From probes to tools

- As the price per photon decreases – ***XFEL will be adopted in many industrial applications***



Industrial XFEL tools (high duty cycle + high efficiency)

Research X-ray light sources (synchrotrons, ICS, XFELs)

Industrial X-ray sources (tubes, industrial accelerators)

XFEL for EUVL

- XFEL science is very mature (long way from the concept to 24/7 users managed light sources)
- The technology has evolved through its R&D phase and entered “HVM” (more ph./$)
- **LCLS-II is a gateway to industrial XFELs**
- EUV lithography is an ideal high added value application to be an early adopter of XFEL tools
- **All the technical prerequisites for EUV lithography XFEL are in place**

US EUV FEL consortium

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- 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

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BERKELEY LAB Lawrence Berkeley National Laboratory

Fermilab

Advanced Energy Systems, Inc.

Argonne NATIONAL LABORATORY

UCLA

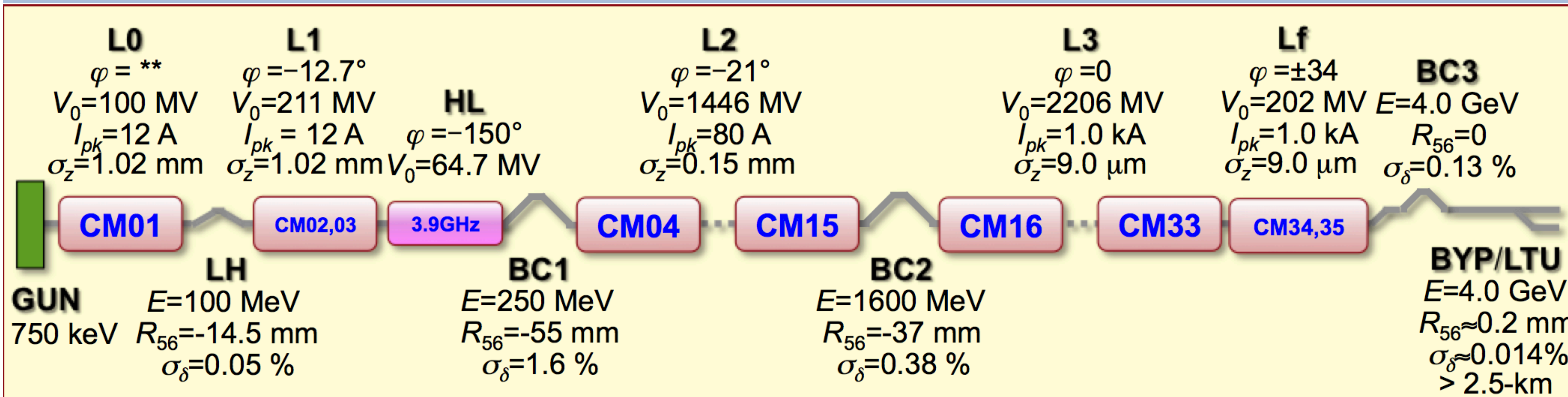
radiasoft

Consortium design strategy

- Identify baseline design that achieves > 10 kW output at 13.5 nm using **demonstrated accelerator technology**
- Performance and reliability are the primary considerations
- Leverage design on the existing projects, infrastructure, resources and expertise

Longitudinal dynamics

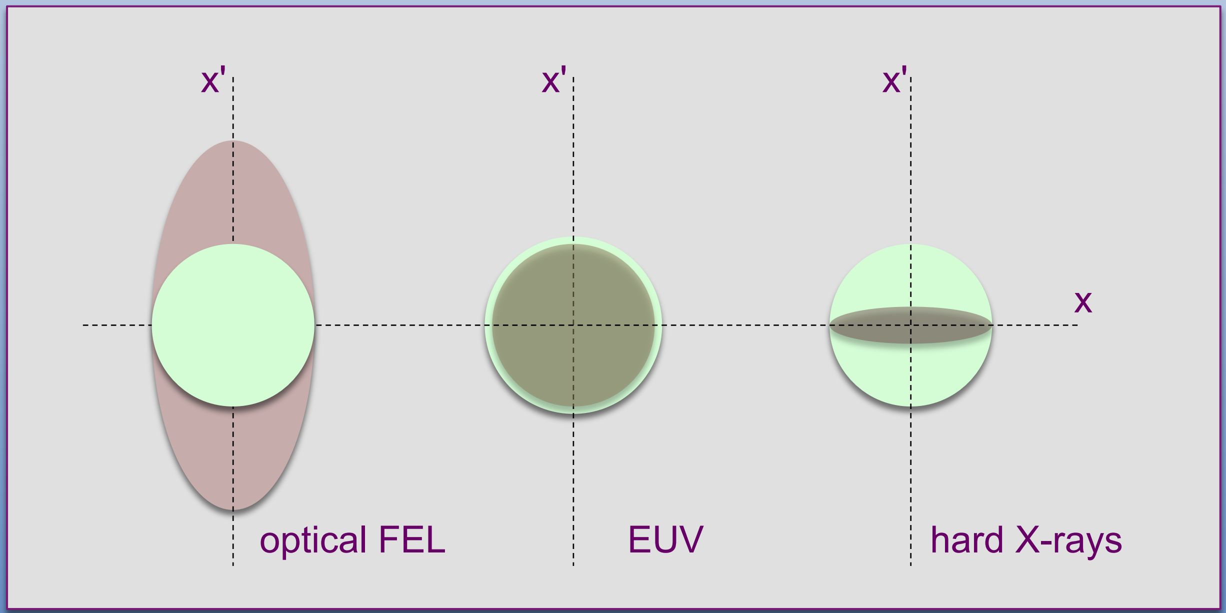
- LCLS-II is a good example: 1MHz SCRF XFEL designed for, but not limited to 1.2 MW beam power
- Factor of ~100 bunch compression without emittance degradation (chicanes, 3.9 GHz cavity, laser heater, dechirping, – unprecedented degree of control over e-beam longitudinal phase space).



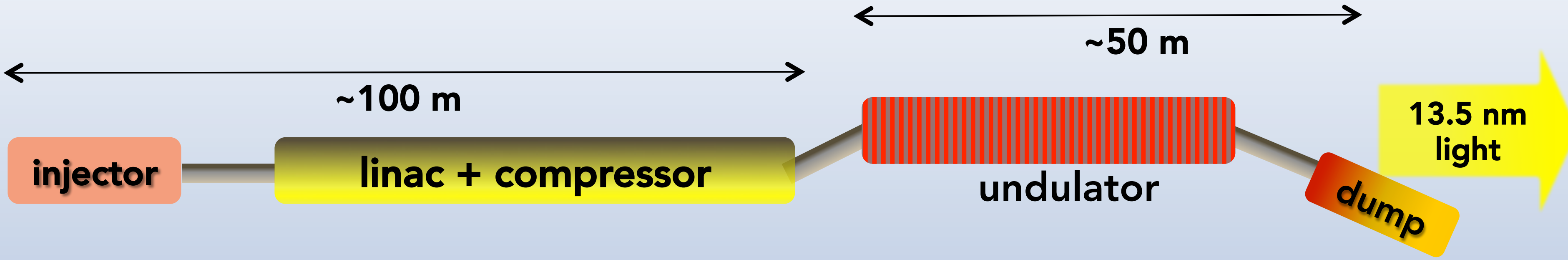
100-pC machine layout: April 24, 2014; v21 ASTRA run; Bunch length L_b is FWHM ** L0 cav. phases: ~(3°, -15°, 0, 0, 0, 0, 15°,0°)

FEL tapering efficiency

- Undulator tapering allows extracting more power out of the e-beam after saturation
- 13.5 nm wavelengths range favors good tapering efficiency, due to optimal transverse overlap
- Initial simulations indicate > 0.5% efficiency



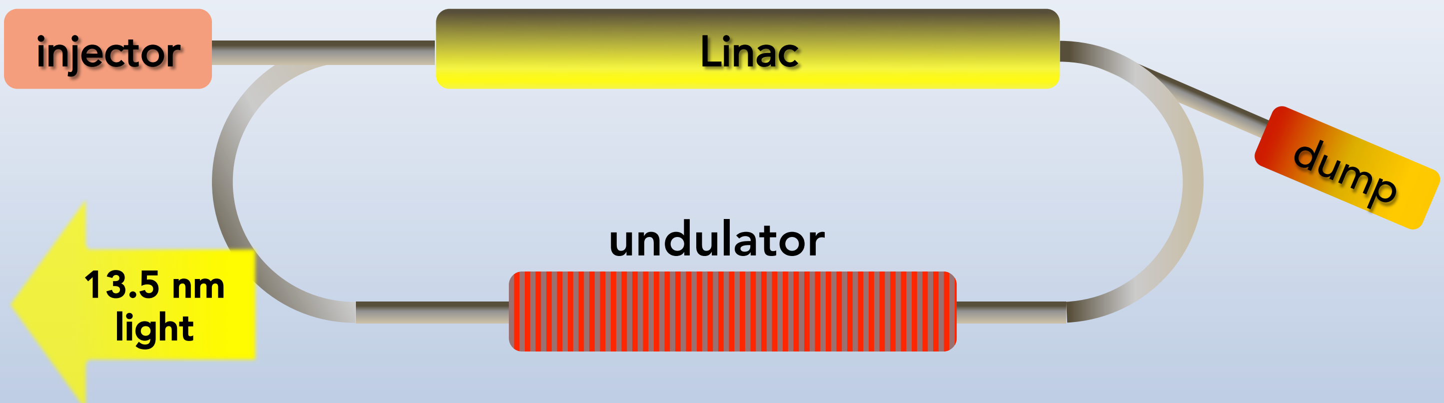
Baseline configuration



- **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

Energy recovery linac



- **Benefits:**
  - More compact configuration
  - Energy recovery
  - Reduced activation
- **Risks:**
  - Poor FEL efficiency
  - Complex beam transport
  - Never demonstrated for XFEL

Avg. EUV power	10 kW
Avg. beam current	15 mA
Avg. beam power	12 MW
FEL efficiency	0.1%
Energy @FEL	650 MeV
Energy recovery?	YES
Power at dump	100 kW

Importance of FEL efficiency

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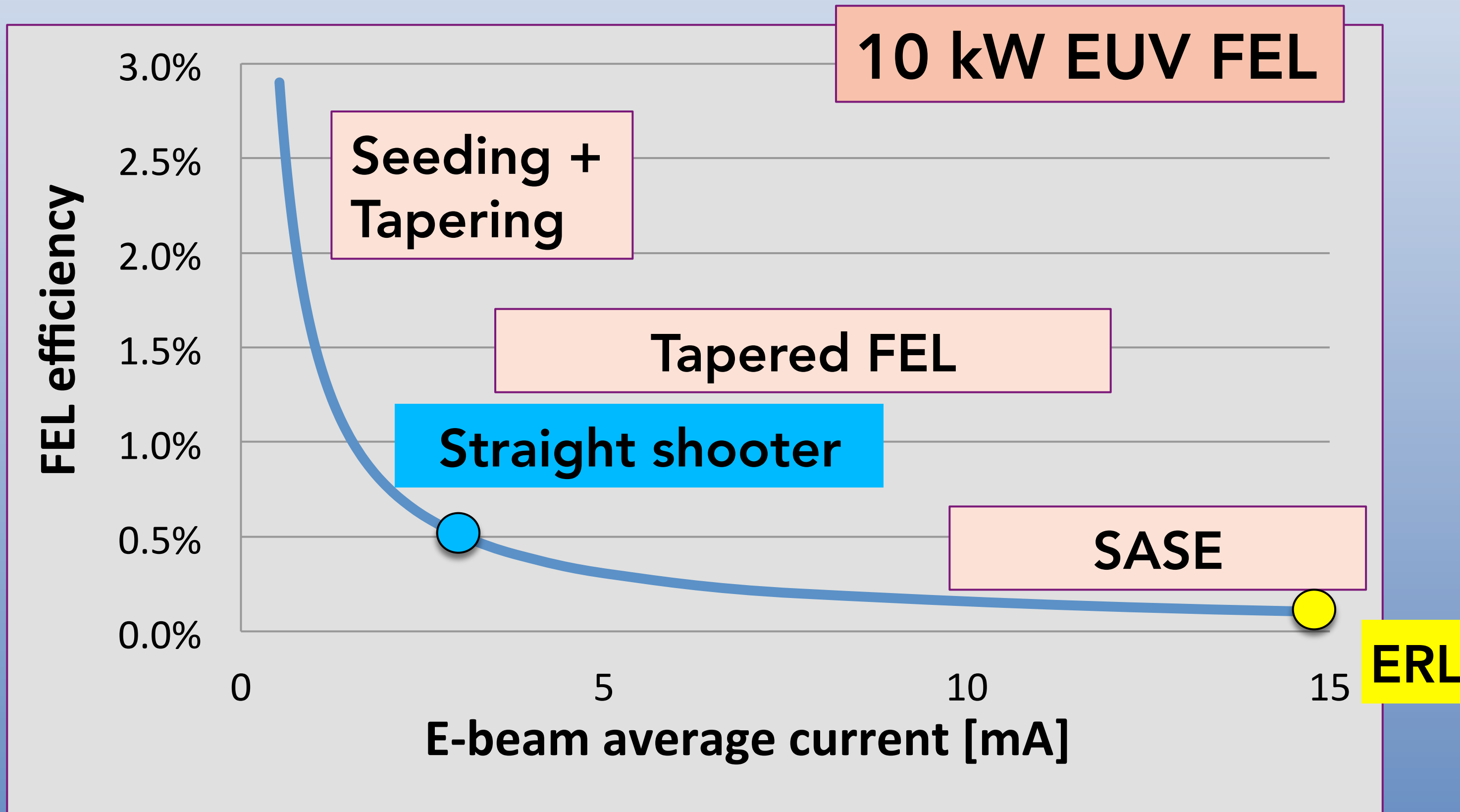
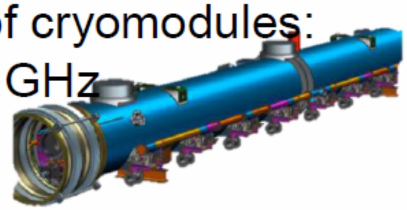
- Smaller average current is always less risk
- Design depends on the limit of FEL efficiency



LCLS-II Collaboration

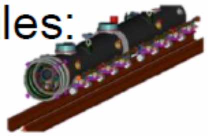
Fermilab

½ of cryomodules:
1.3 GHz

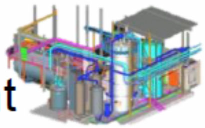


Jefferson Lab
EXPLORING THE NATURE OF MATTER

½ of cryomodules:
1.3 GHz

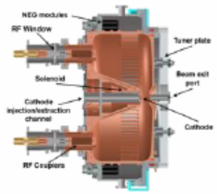


Cryoplant

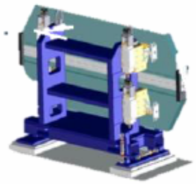


BERKELEY LAB

e$^-$ gun & associated injector systems



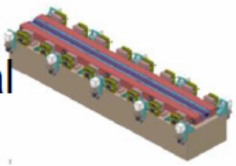
Undulators



Argonne NATIONAL LABORATORY

Undulator Vacuum Chamber

Undulator R&D: vertical polarization



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R&D planning, prototype support
e$^-$ gun option

Example: LBNL CW gun

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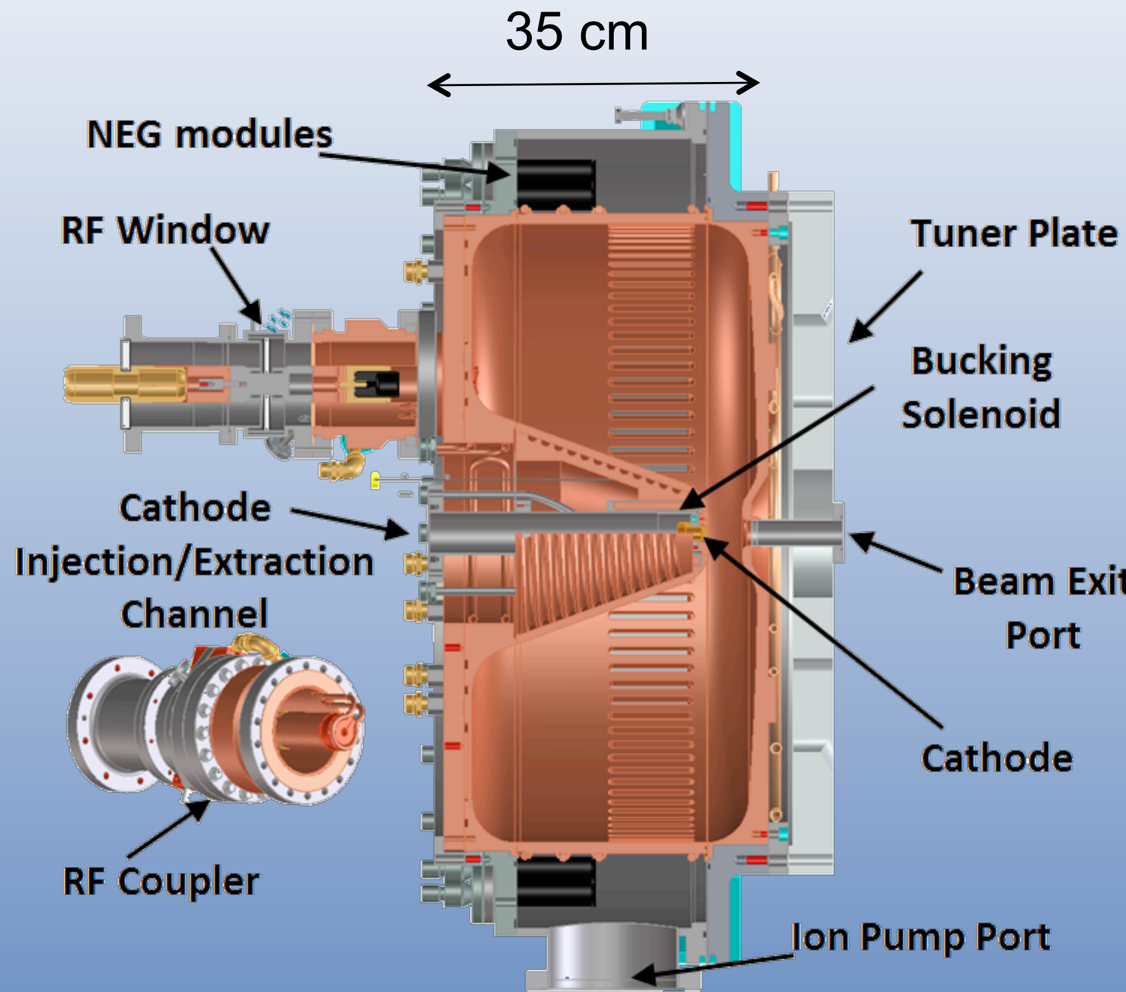
- The cavity structure is large enough to withstand the heat load and operate in CW.
- High repetition rate beams.
- High vacuum conductivity-long cathode lifetime.
- Based on mature RF and mechanical technologies.



SCRF Program at Fermilab

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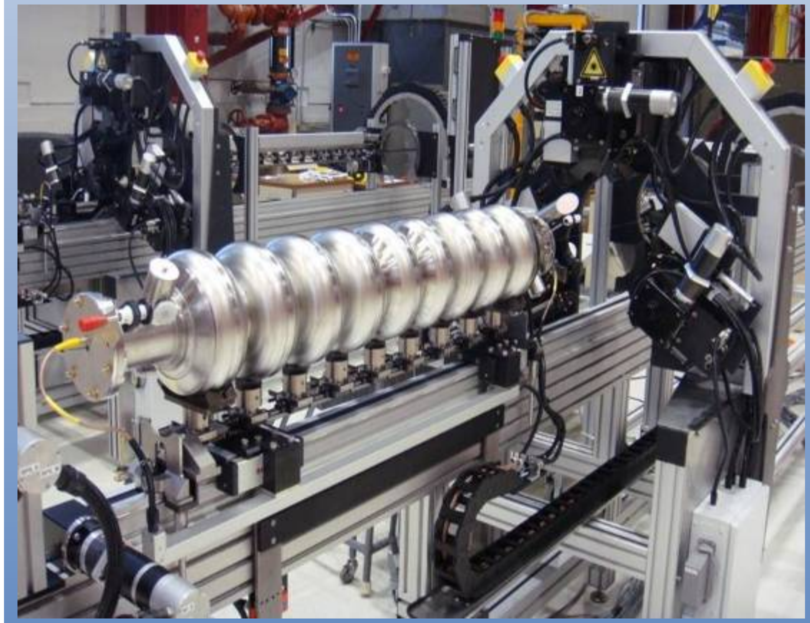
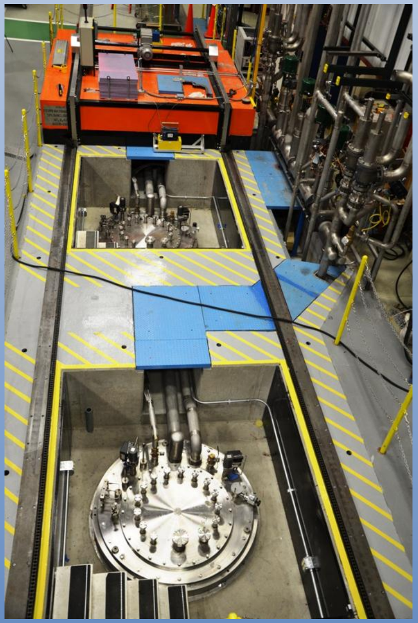
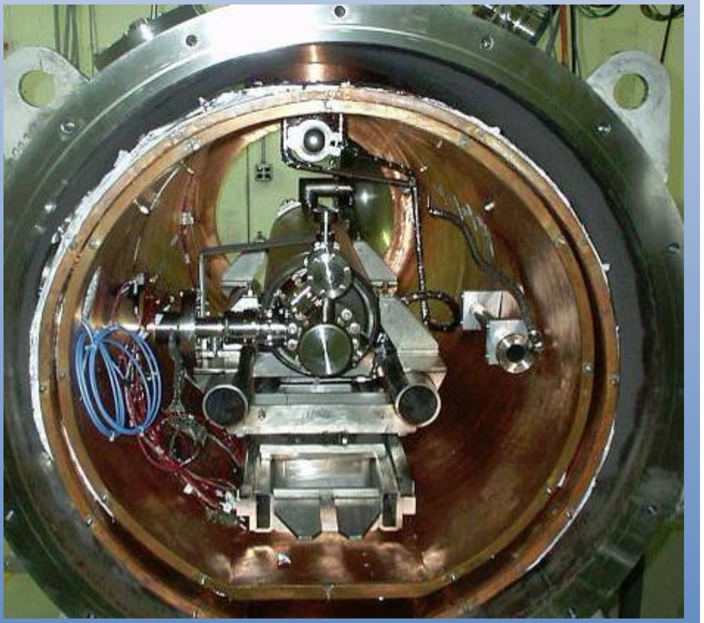
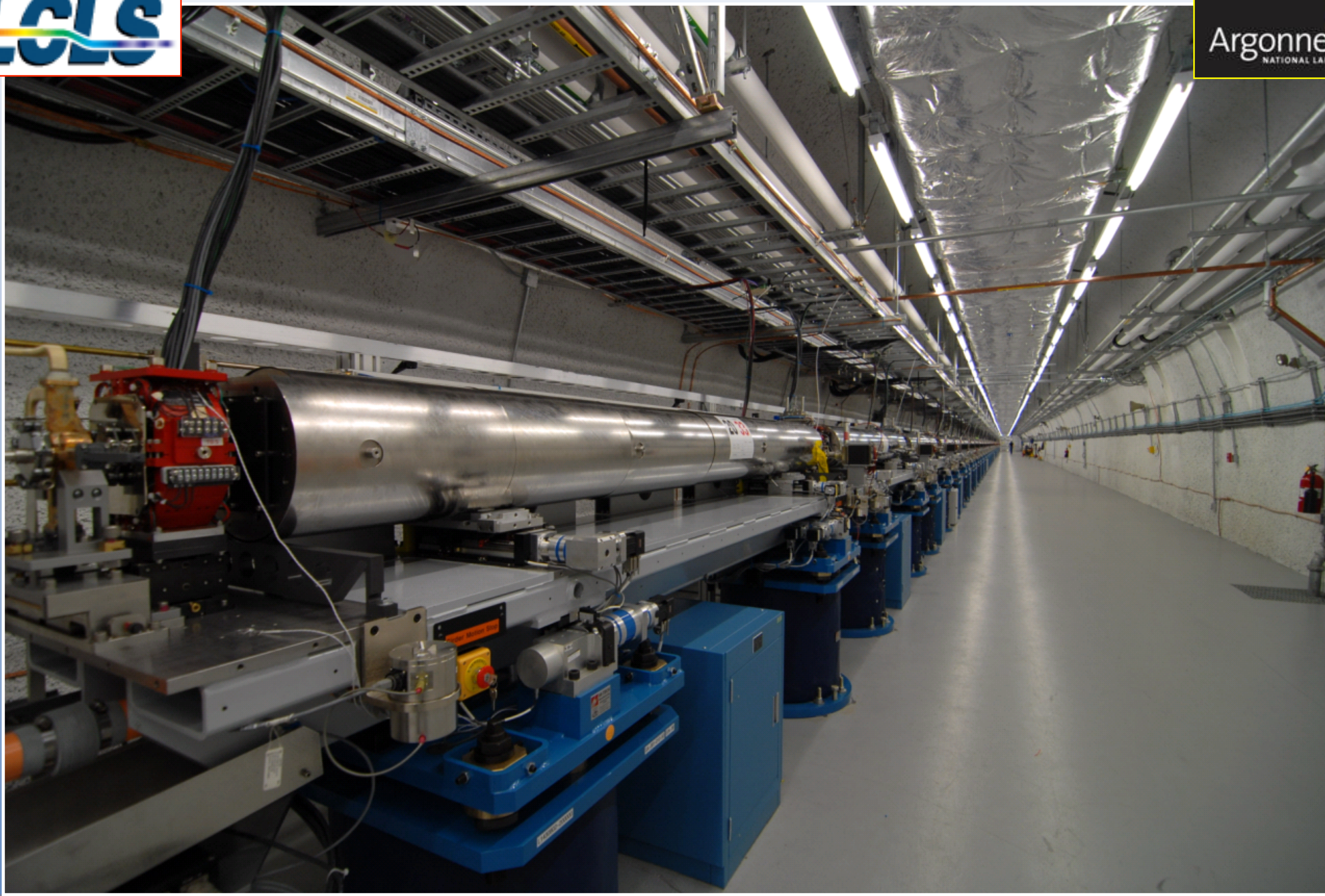
- Two major efforts in progress
  - R&D for PIP-II 800 MeV H- SRF linac (HEP)
  - Fabrication of 17 CW Cryomodules for LCLS-II
- Recent improvement in SCRF cavity surface processing enabled large increase in Q-factor







ANL undulator technology



Status summary

10 kW industrial EUV FEL can be developed with minimal risk using the existing technological base:

- High Brightness CW Injector
  - APEX photoinjector under construction for LCLS-II
  - DC Gun-Cornell (shown 80 mA average current)
- CW SCRF cryomodules are under construction at Fermilab and JLAB for the LCLS-II
- Hybrid permanent magnet technology for undulators is mature (kilometers has been built)
- Accelerator design: XFEL physics and beam dynamics are well understood, supported by high fidelity numerical tools, and validated