LCLS-II and Free electron laser drivers for EUV Lithography

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GlobalFoundries reports* Fab point of view of why Free-electron-laser (FEL) EUV sources should be considered

Hosler *et al,* report LPP concerns:
- Sn debris dynamics
- Back reflection
- Reliability
- Scaling to higher energy 1kW/tool
- 10 x1 kW scanners 95% availability

* E. Hosler, *et al.*, “Considerations for a free-electron laser-based extreme-ultraviolet lithography program”, Proc. of SPIE Vol. 9422, 94220D, 2015

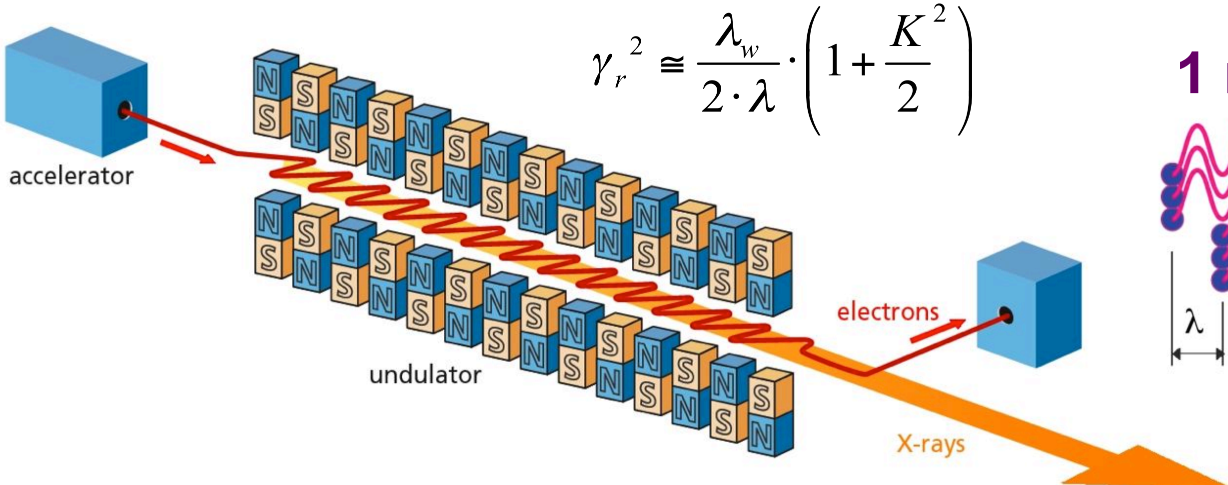
Summarizes various FEL architectures for 1 machine to deliver 13.5 nm light to multiple tools for HVM

Our consortium is taking a comparative look at a “straight shooter” FEL

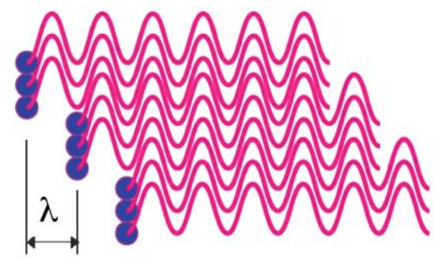
Basic operating principle of short wavelength FELs

FEL interaction: coherent amplification of undulator radiation

$$\gamma_r^{\,2} \cong \frac{\lambda_w}{2\cdot\lambda}\cdot\left(1+\frac{K^2}{2}\right)$$



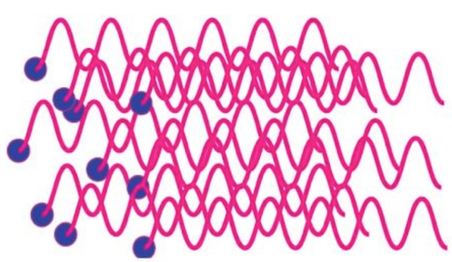
1 mA -> kWs



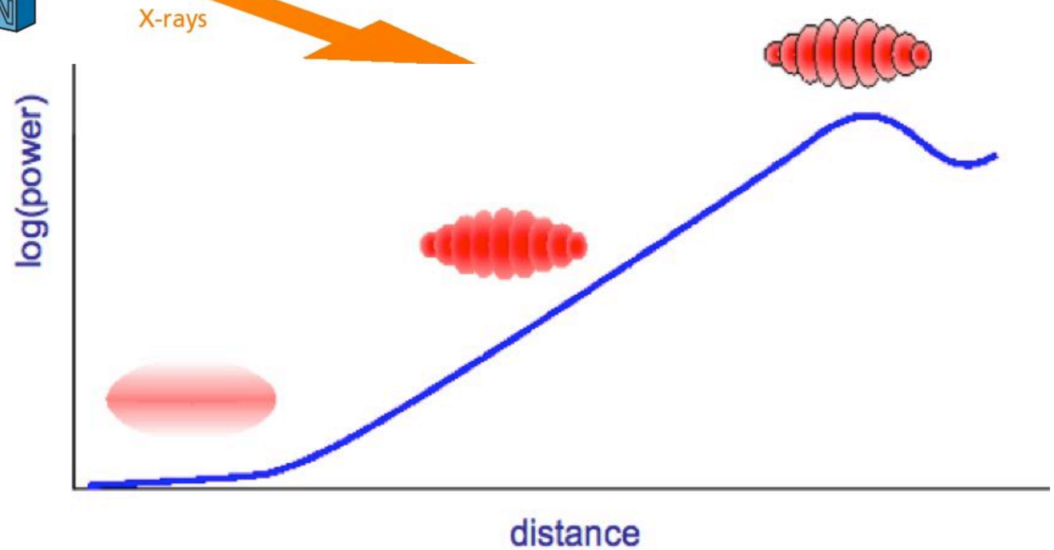
$$E = N\,E_1$$

$$P = N^2\,P_1$$

1 mA -> 1 mW

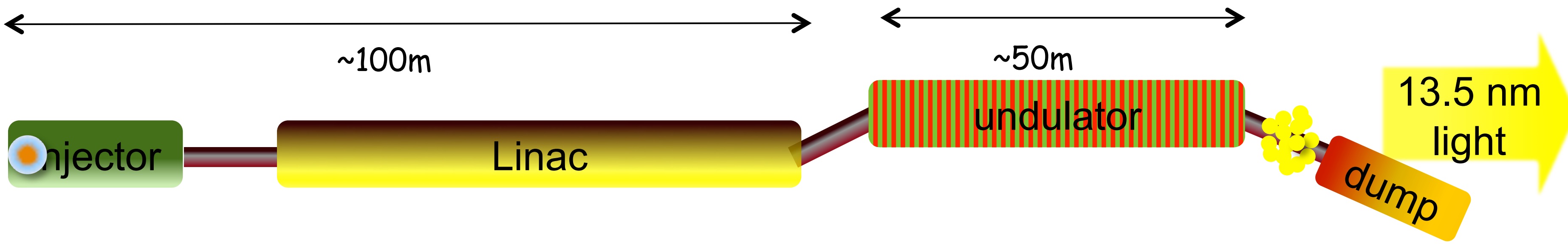


$$P = N\,P_1$$

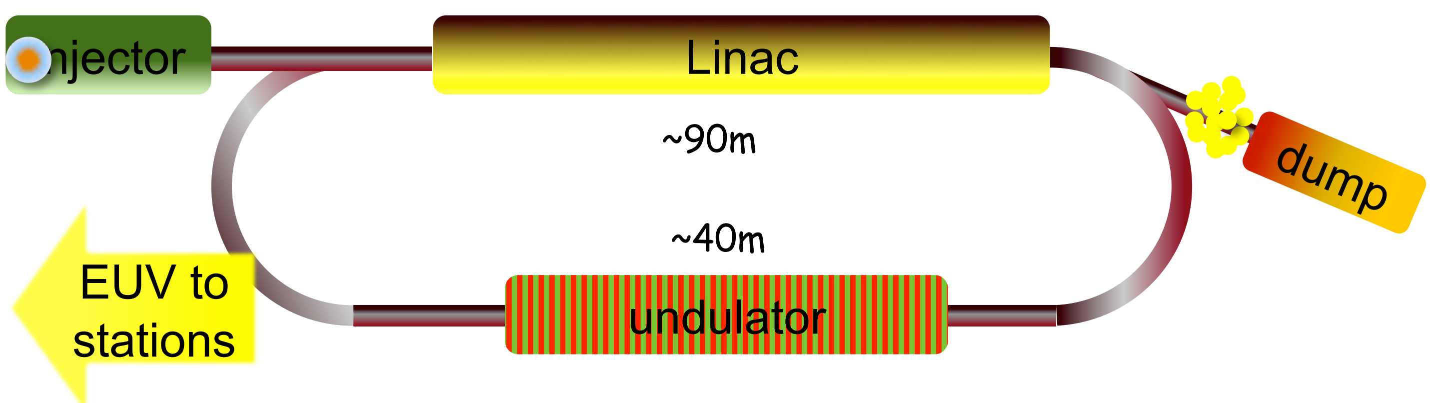


Two Baseline EUV FEL topologies: Need MW electron beam power to get 10 kW 13.5 nm light: Efficiencies <1%.

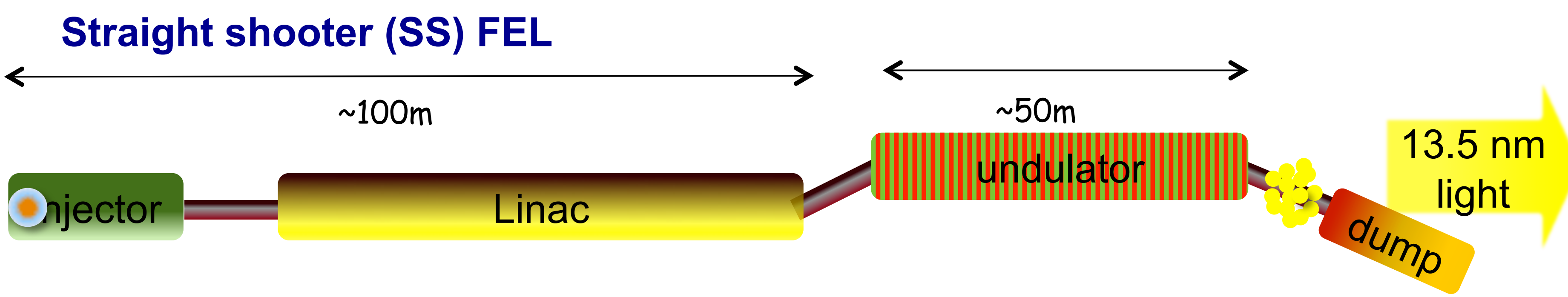
Straight shooter (SS) FEL



Energy Recovery Linac (ERL) FEL



Straight Shooter



Benefits:

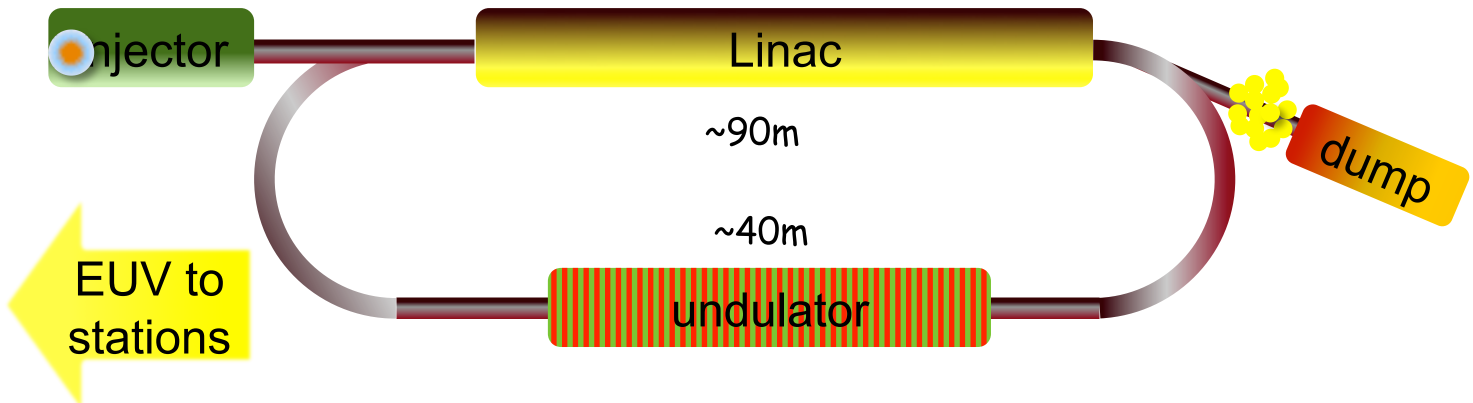
- Proven approach, leveraged on all existing and planned XFELs
- All components are demonstrated and most are industrialized
- Enables highest FEL efficiency
- Relaxed injector and machine protection requirements
- Upgradable (modular architecture)

Disadvantages:

- High power beam dump, increased capital cost of RF system

Energy Recovery Linac

Energy Recovery Linac (ERL) FEL



Benefits:

- Relaxed beam dump requirements
- Beam energy recovery (reduced cost of the RF system)
- Demoed at IR

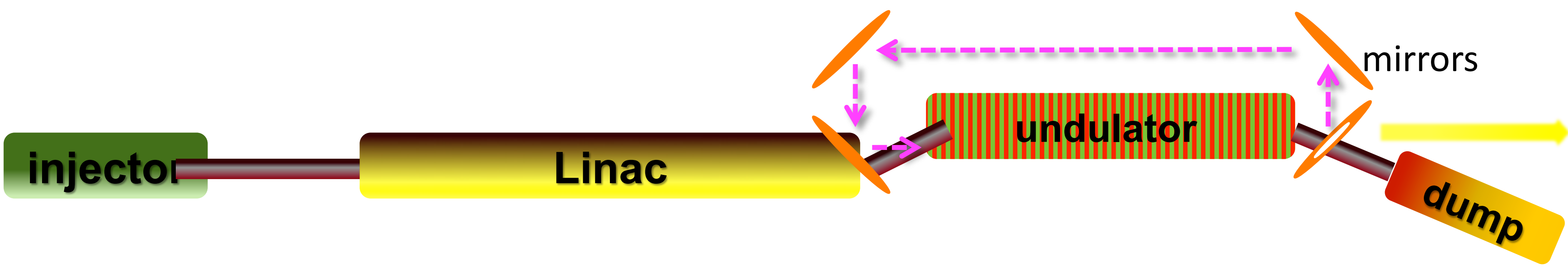
Disadvantages:

- Need to optimize FEL and ERL simutaneously
- Higher beam recirculating power (engineering risk)
- **Never demonstrated at short wavelengths**

Straight Shooter offers most straightforward path to higher FEL efficiency

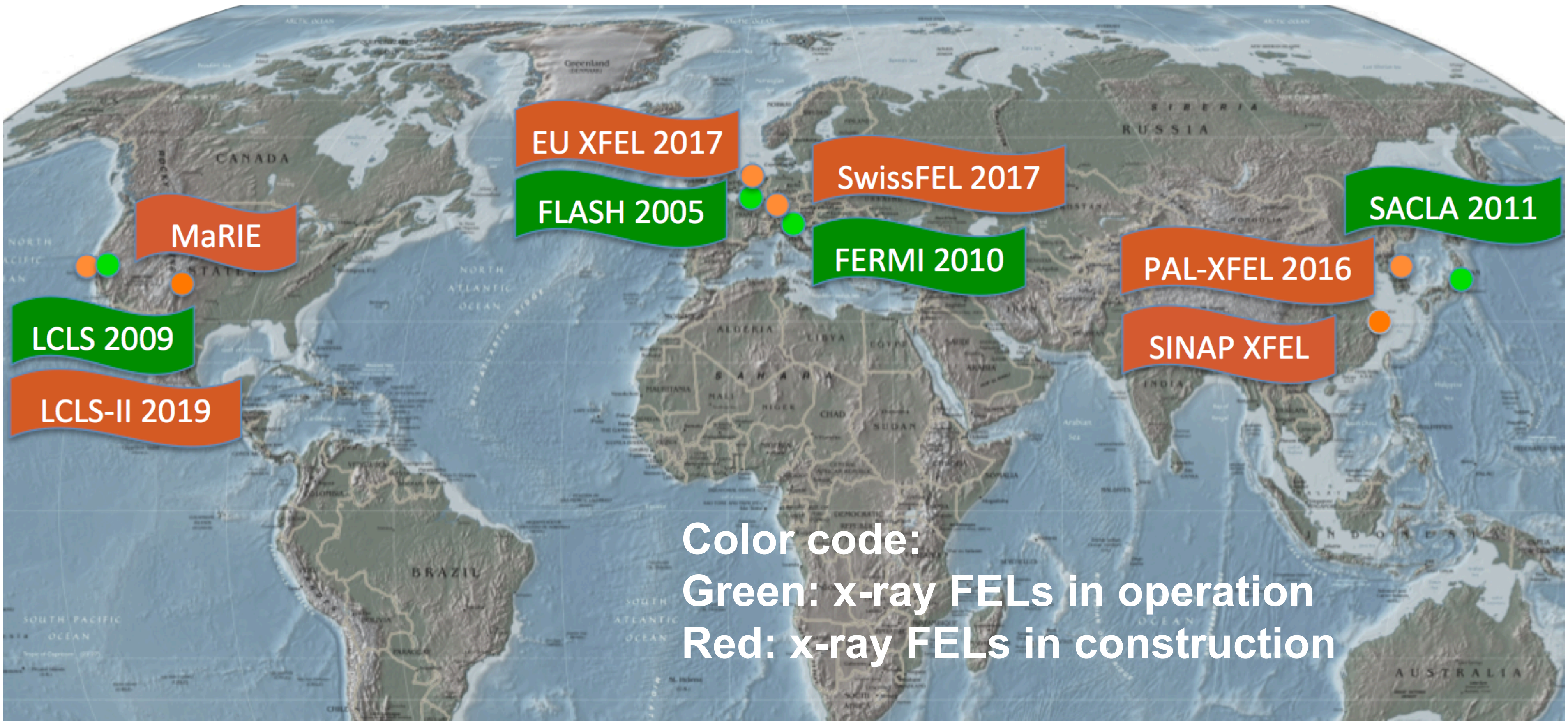
Increasing FEL efficiency allows lower e-beam power.

- Several techniques under study in the FEL community.
- Example: regenerative amplifier, (others self seeding, tapering)

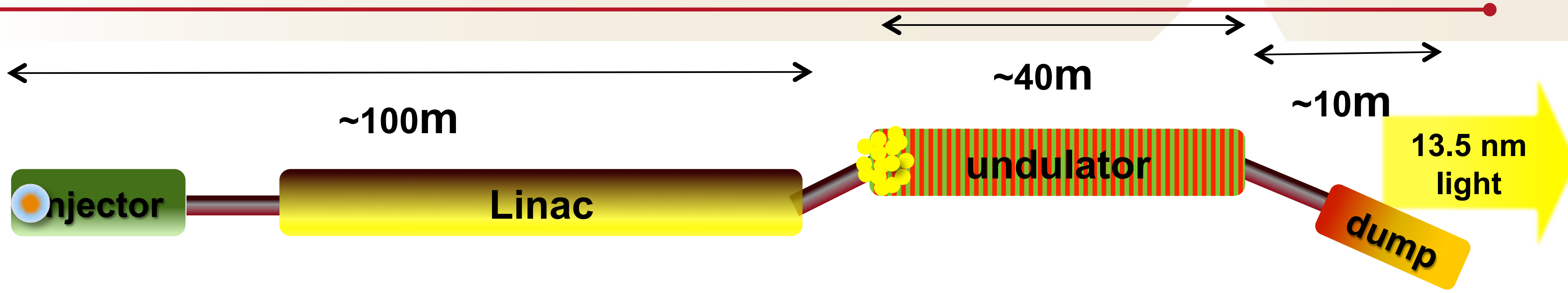


Improved FEL efficiency >1%.

X-ray FEL sources have been thoroughly tested at many facilities, and many more are under construction



Our baseline configuration is a 10 kW Straight Shooter



Based on demonstrated accelerator design and technologies

✓High rep-rate photoinjector

✓CW Superconducting Linac

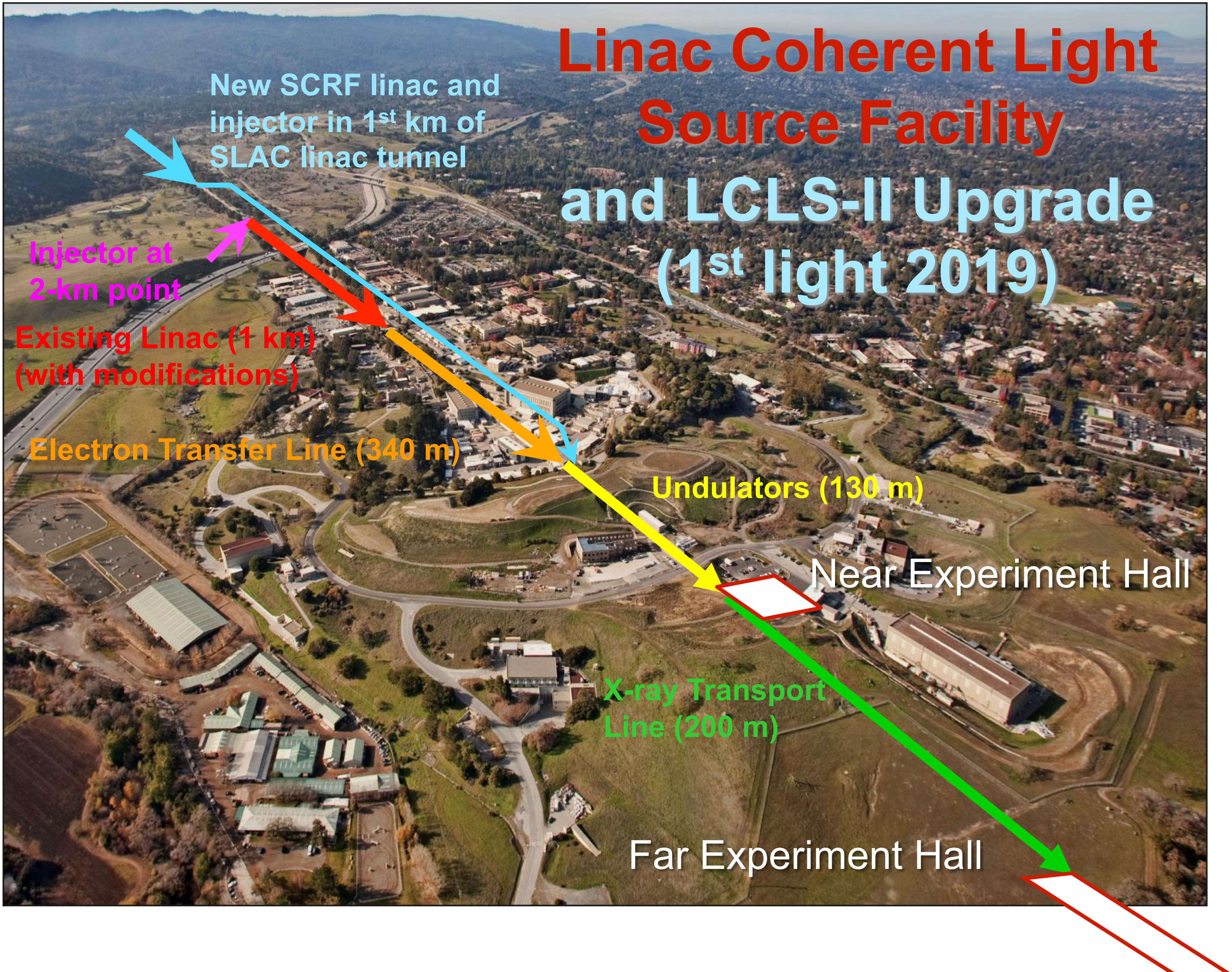
✓Permanent Magnet Undulator

✓High power beam dump

Natural extension of LCLS-II technology.
Lowest risk option. Path to higher efficiency.

US EUV consortium interested in FEL solution to EUV Lithography

Institution	Expertise and Technology
SLAC	**LCLS-II**, FEL physics, beam physics, accelerator technology
LBNL	CW injector, undulators, EUV optics, FEL physics, beam physics
Fermilab	**ASTA**, SCRF physics and technology
Argonne	Undulators, vacuum system, diagnostics
Cornell	CW injector, CW RF, undulators, diagnostics
UCLA	FEL physics, beam physics
RadiaBeam	Diagnostics and instrumentation
AES	SCRF cavities fabrication
RadiaSoft	Numerical codes development

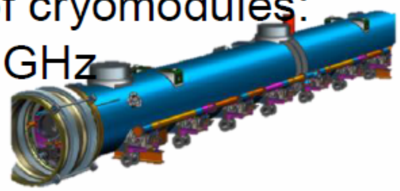

Linac Coherent Light Source Facility
and LCLS-II Upgrade
(1st light 2019)
New SCRF linac and injector in 1st km of SLAC linac tunnel
Injector at 2-km point
Existing Linac (1 km) (with modifications)
Electron Transfer Line (340 m)
Undulators (130 m)
Near Experiment Hall
X-ray Transport Line (200 m)
Far Experiment Hall

Project Collaboration

SLAC

Fermilab

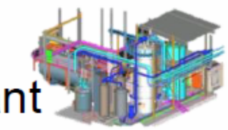
½ of cryomodules: 1.3 GHz



Jefferson Lab
EXPLORING THE NATURE OF MATTER

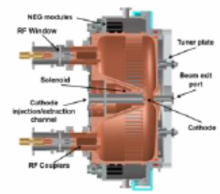
½ of cryomodules: 1.3 GHz

Cryoplant

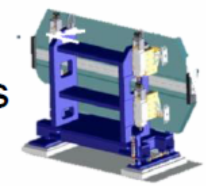


BERKELEY LAB

e⁻ gun & associated injector systems



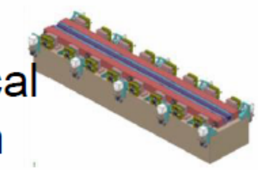
Undulators



Argonne NATIONAL LABORATORY

Undulator Vacuum Chamber

Undulator R&D: vertical polarization

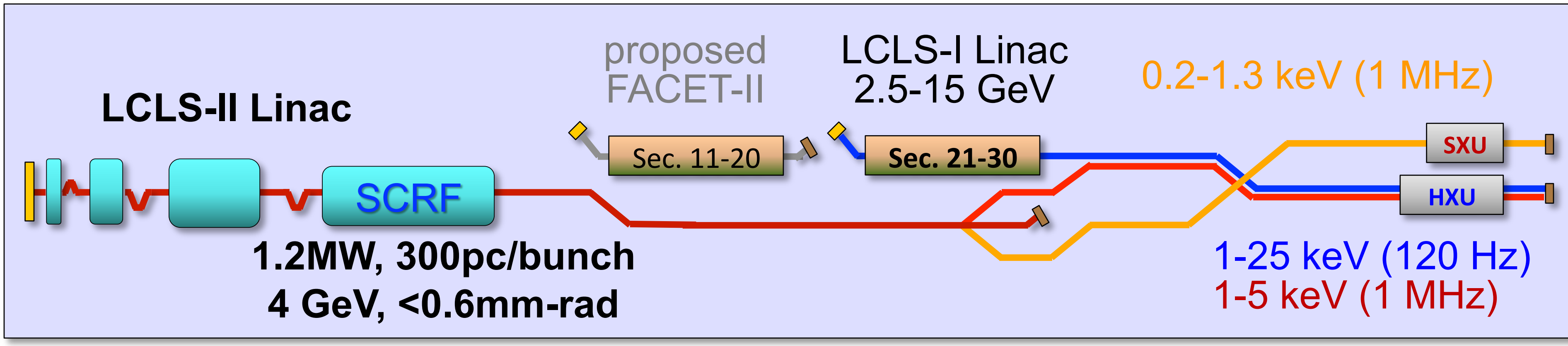


CORNELL UNIVERSITY FOUNDED A.D. 1865

R&D planning, prototype support
e⁻ gun option

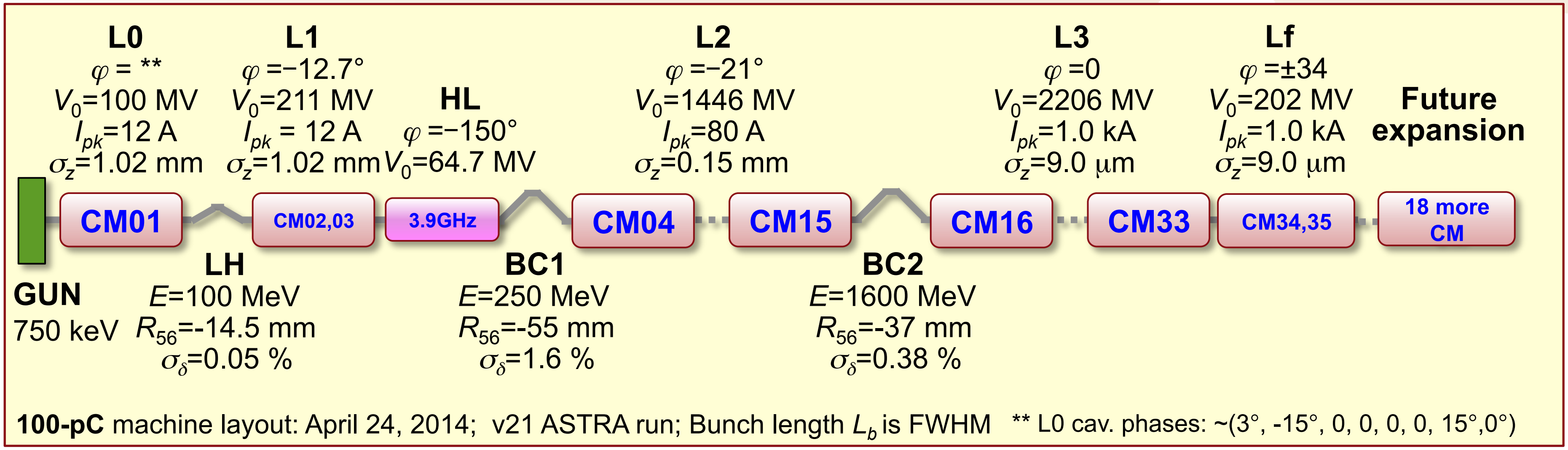
LCLS-II Accelerator Layout

- Now two sources: MHz rate SCRF linac and 120 Hz Cu LCLS-I linac
- Hard and Soft X-ray undulators



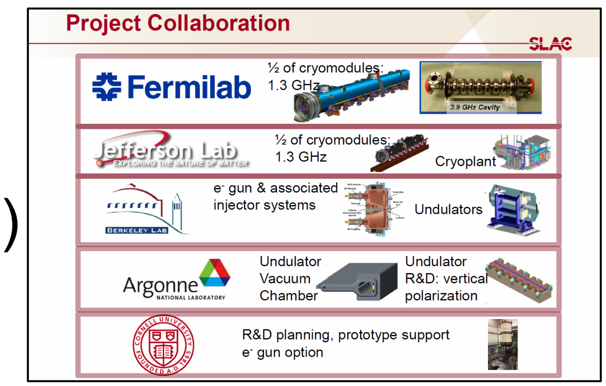
Undulator	SC Linac (up to 1 MHz)	Cu Linac (up to 120Hz)
Soft X-ray	0.20 - 1.3 keV with >100 Watts	
Hard X-ray	1.0 - 5.0 keV with >20 Watts	1 - 25 keV with mJ-class X-ray pulses

LCLS-II SCRF beamline layout: lasing requires electron beam dynamics control

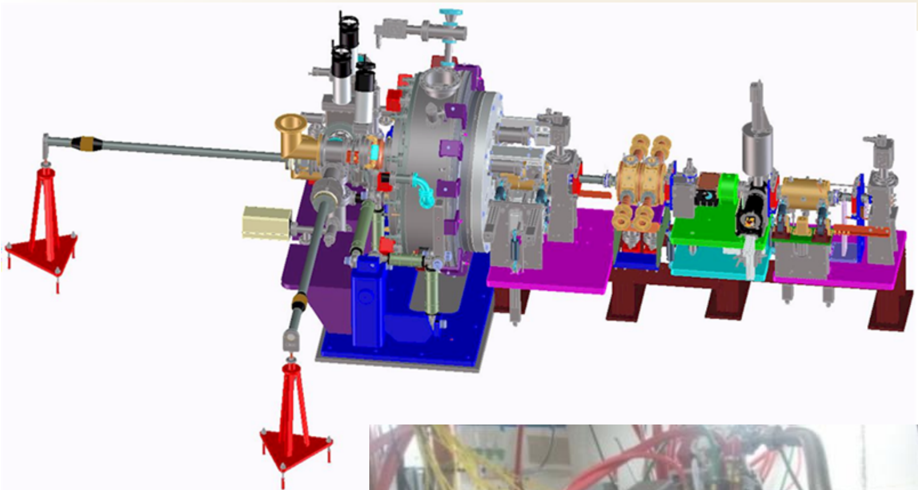


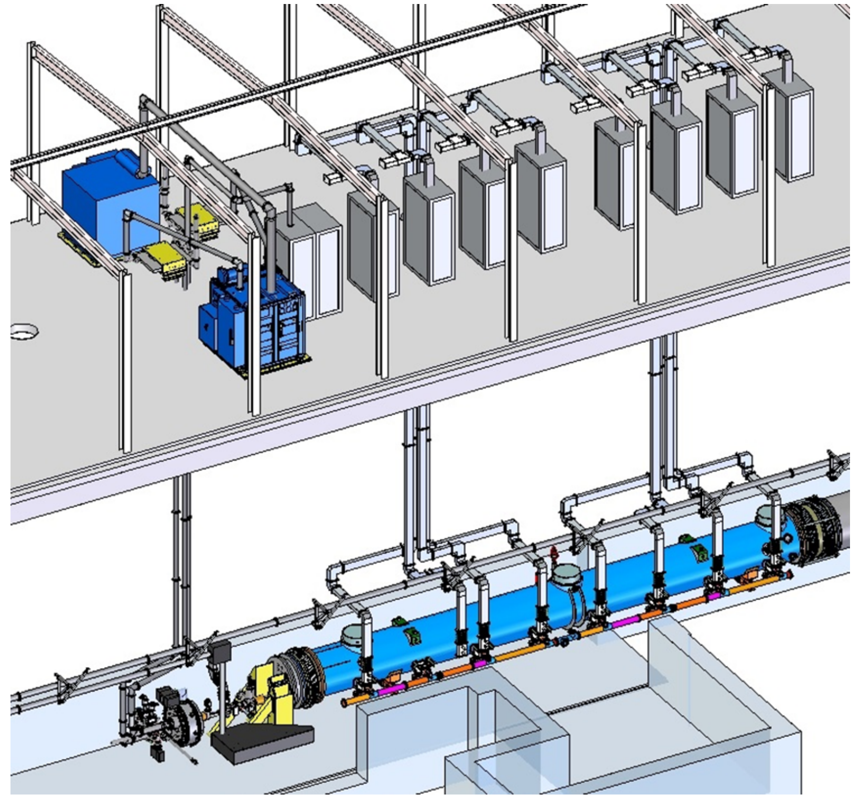
Topics for high average power:

- CW superconducting RF system
- High brightness CW injector
- Variable gap undulators (fixed gap for EUV)
- High beam power
- Dynamics in high brightness, low-energy electron beams



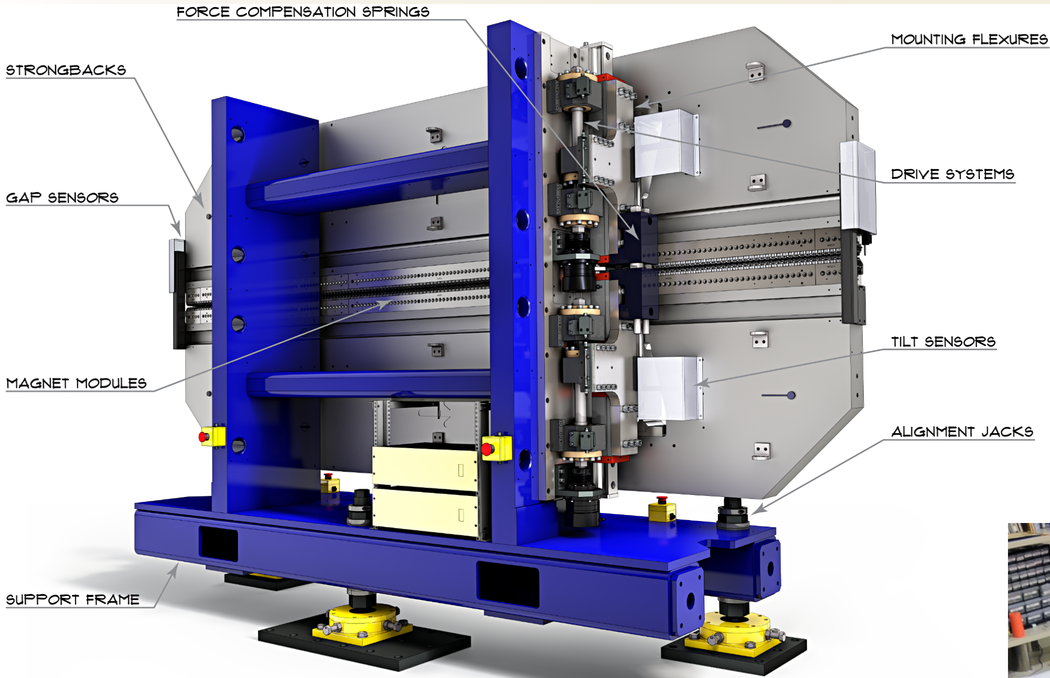
LCLS-II Electron Injector uses a 750 kV VHF RF gun based on the APEX project gun at LBNL





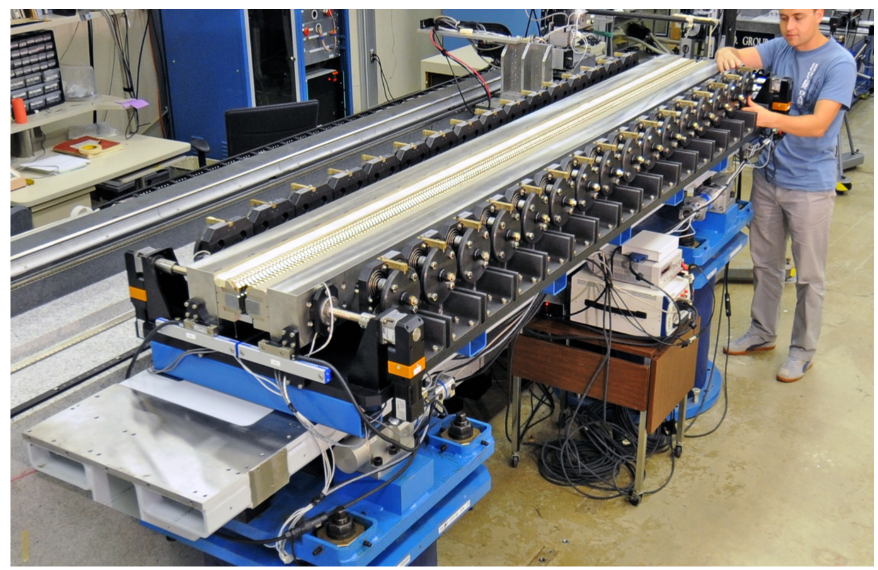
- Need gun both delivering high average current mA and low emittance.
- Prototypes built at LBNL and Cornell (DC 450 kV)
- Tests to be completed in FY15

Variable Gap Hybrid Undulators
Ongoing Development at LBNL and ANL

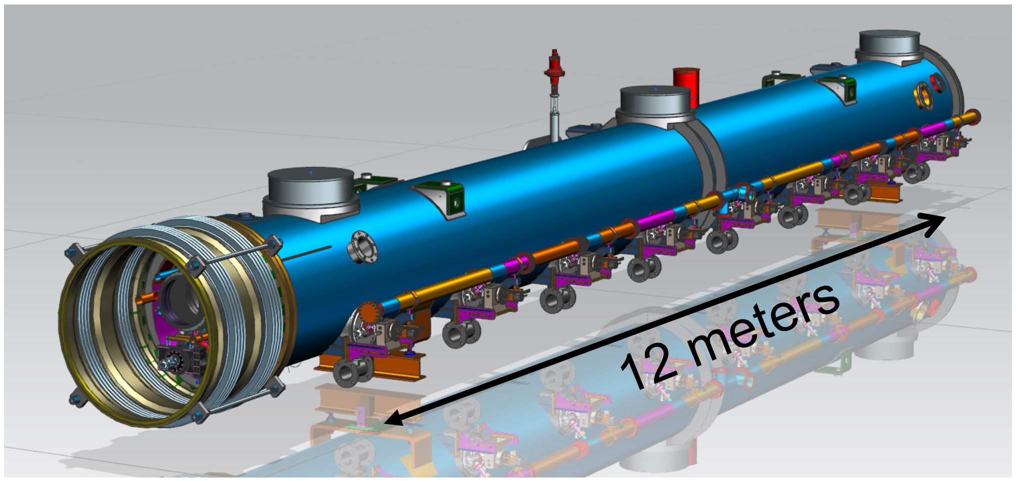


Provide greater wavelength tuning flexibility
Two undulators with total length of ~230 m
1st production in FY17

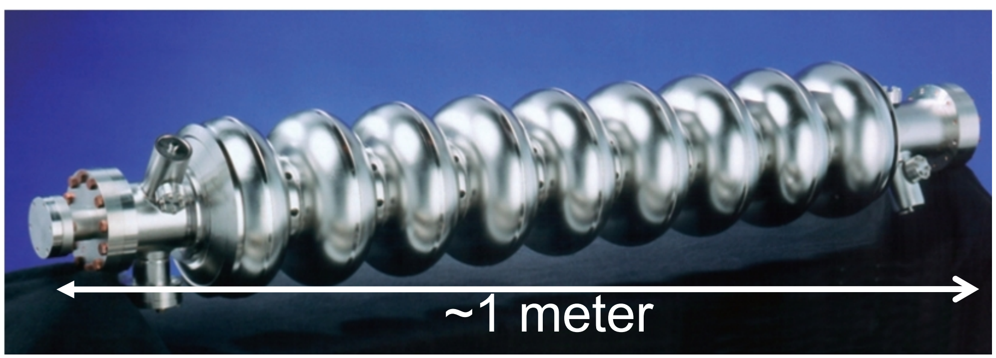
Developing two alternates: Superconducting undulator (SCU) and a Horizontal gap vertically polarized undulator (VPU). See: E. Gluskin,



LCLS-II Cryomodule and superconducting rf cavities
1.3 GHz, CW operation



Crymodules will be similar to EuXFEL

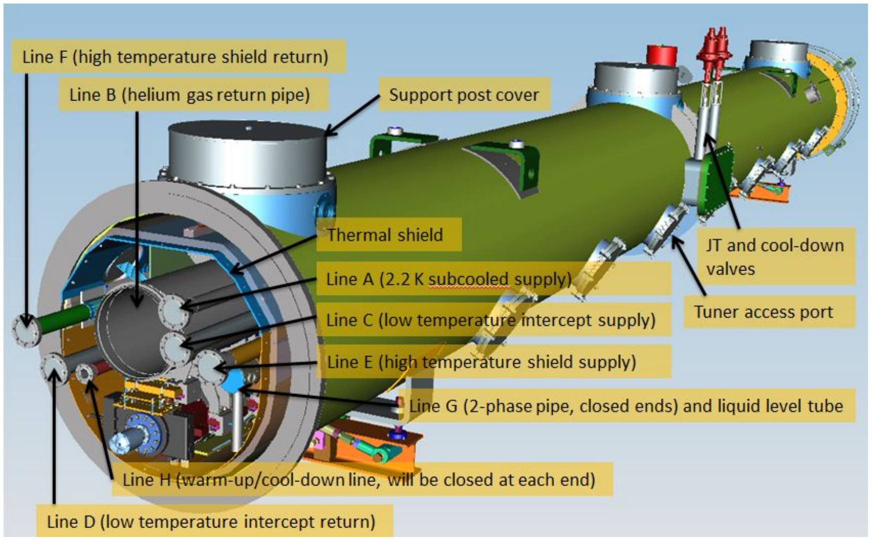


Backbone of the LCLS-II accelerator are the 9-cell 1.3 GHz superconducting rf cavities

LCLS-II RF System

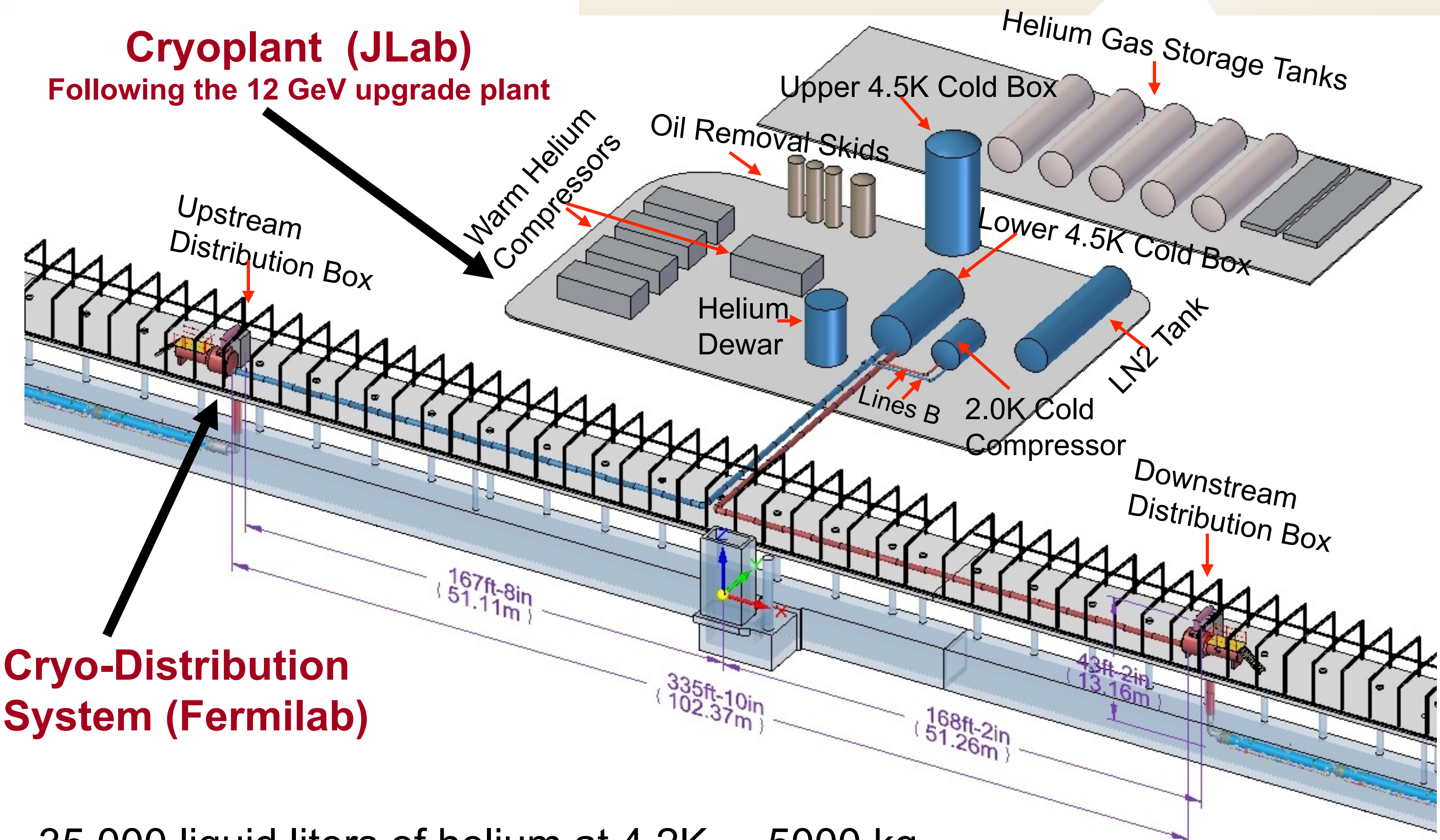
SCRF Cryomodule
- ~13 m in length
- Contains 8 SCRF cavities operating at 2°K
- LCLS-II will use 35 modules
- Two prototypes in FY16

RF Power Source
- 280 4kW 1.3 GHz solid-state rf sources (SSA's)
- 21 prototypes to be evaluated in FY16



10kW SSA at ELBE, Dresden

Cryoplant and Cryogenic Distribution System
Exploring single and double cryoplant options

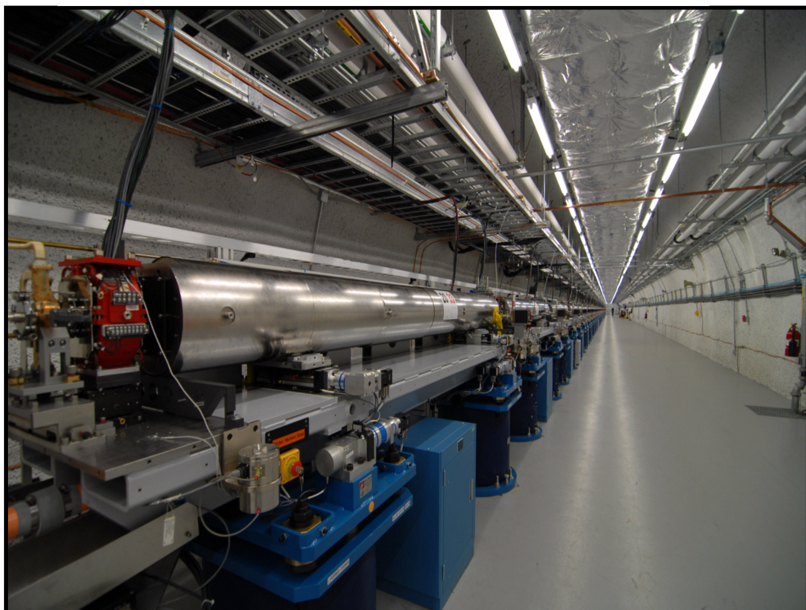


35,000 liquid liters of helium at 4.2K, ~5000 kg

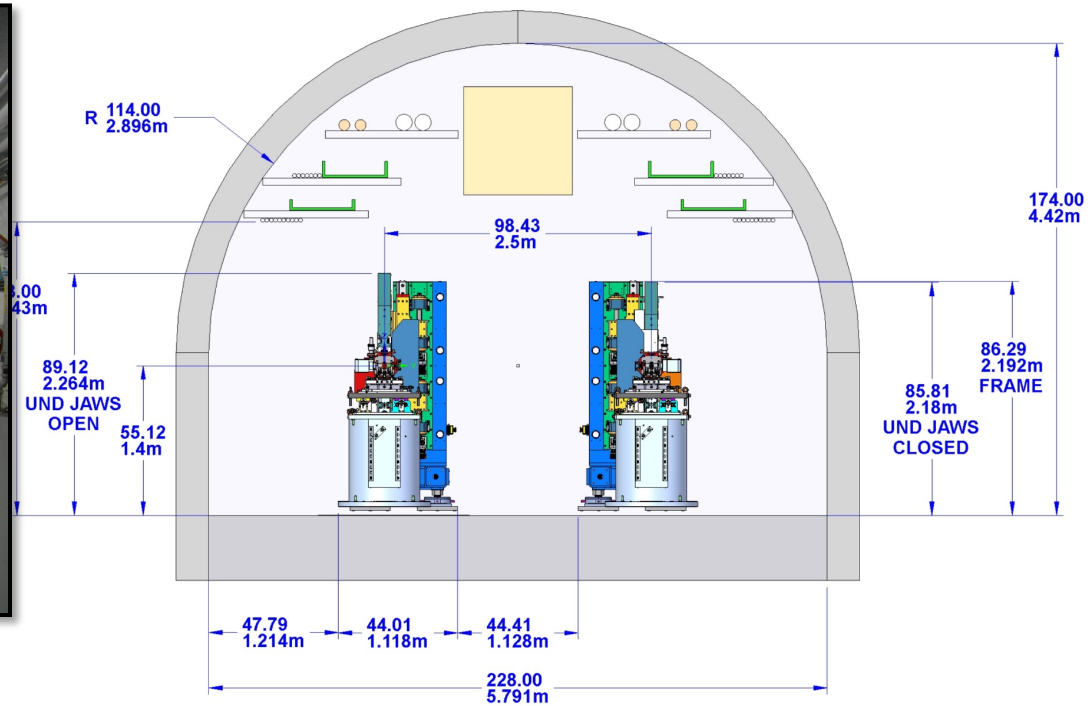
LCLS-II Undulator Hall

- The existing LCLS undulator will be removed from the hall
- LCLS-II adds two new variable gap undulators
  - X-ray energy tunability at a fixed electron beam energy

Existing LCLS Undulator



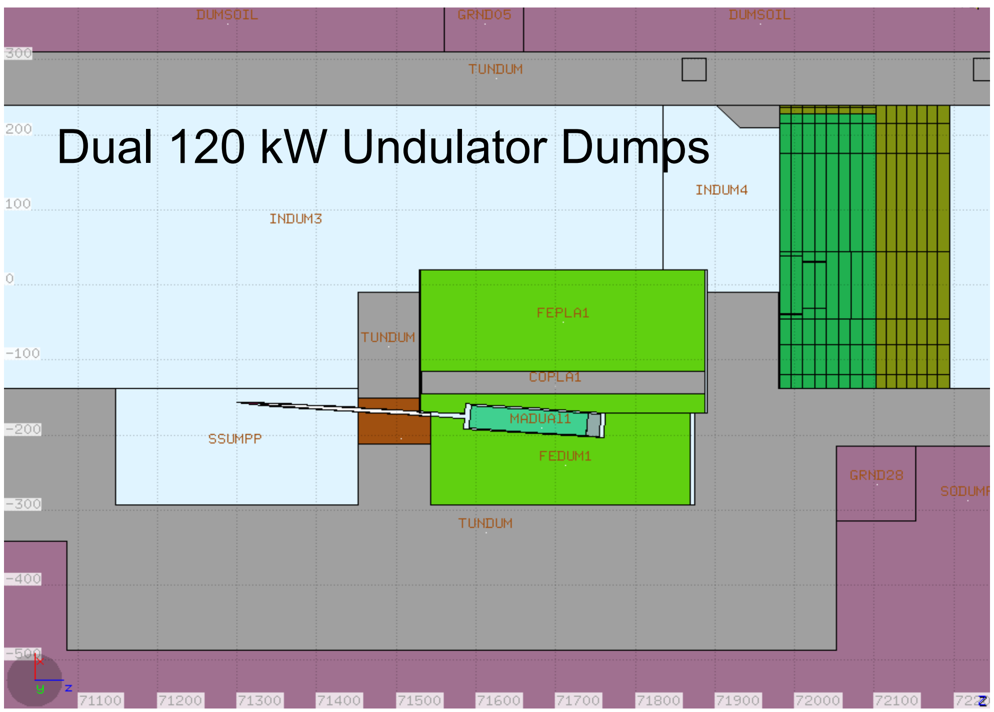
Two new LCLS-II Undulators in the tunnel

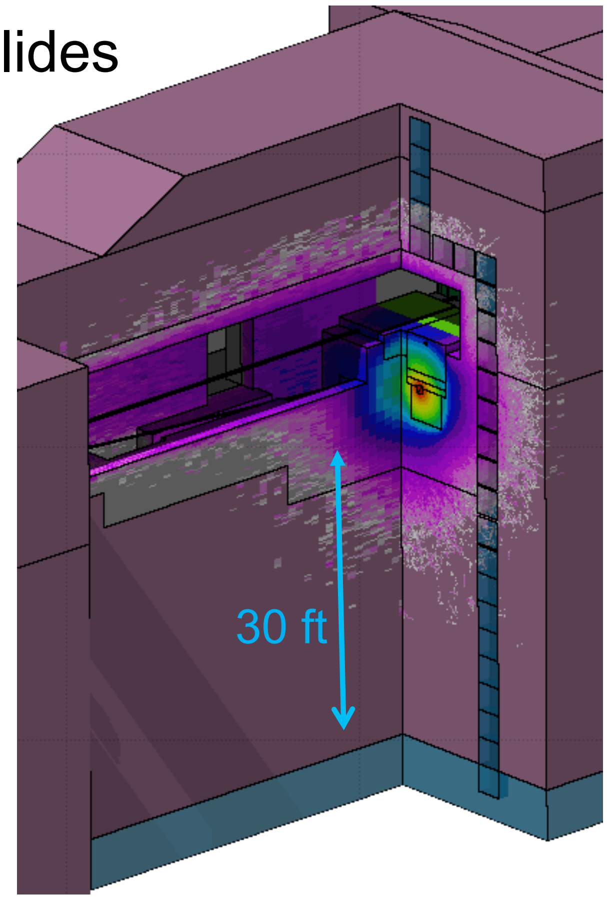


MW-class Beam Dumps

SLAC has a number of MW beam dumps constructed over decades of operation

- Require separated water systems with tritium separation and careful treatment of other radionuclides
- Designed to be replaceable





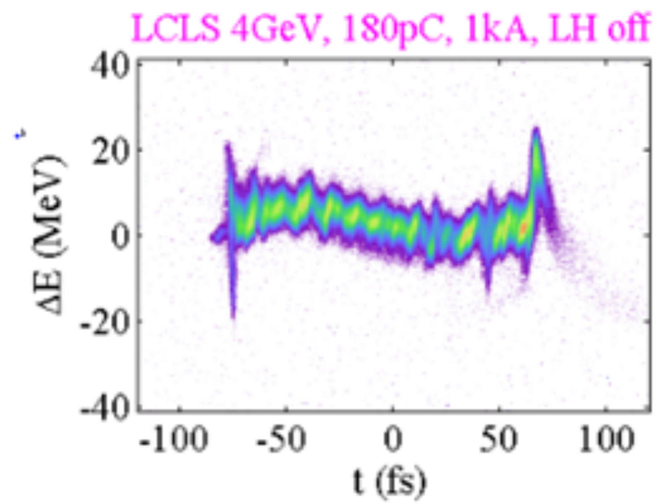
Start-to-End FEL Modeling

FEL physics is well understood **provided** beams are well modeled

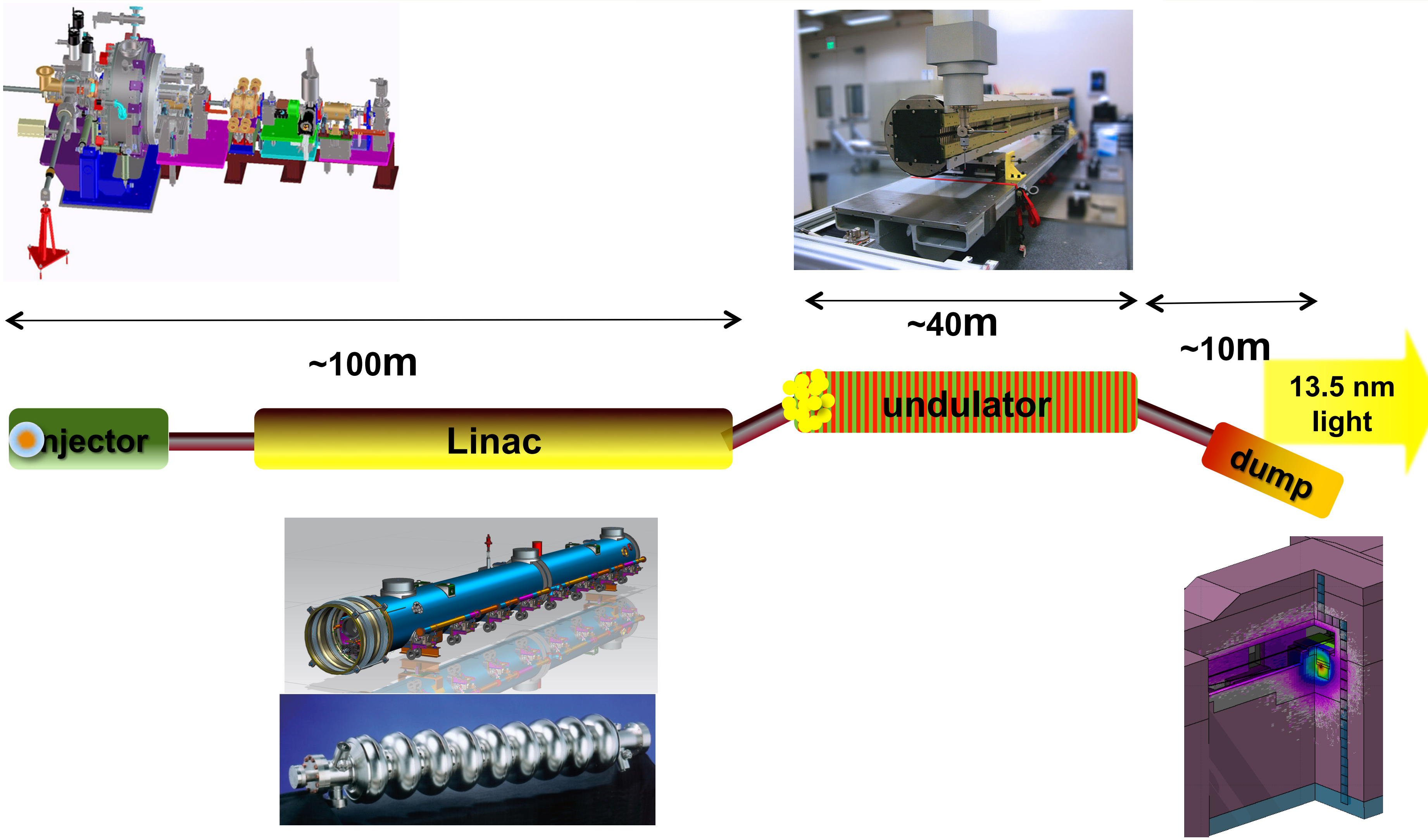
LCLS-II is being extensively modeled using 3D PIC codes

High brightness beams at modest energy and long transport → longitudinal instabilities

Simulations are being benchmarked using the LCLS at low energy



Re-purpose LCLS-II technologies for EUV: 800MeV, 2cm period undulator, ~15 MeV/m



Summary

- LCLS-II will have developed all major technical accelerator systems for an EUV FEL by FY17

- Lowest risk option for a high power EUV-FEL is a straight-shooter

- Optimized 13.5 nm FEL would be 4~5 times lower energy with simpler beam physics than LCLS-II

- Higher FEL efficiency via tapering strong possibility for reducing total electron beam power and increasing reliability

- Consortium is well positioned to couple the LCLS-II momentum to industrial EUV FEL development

Thanks.