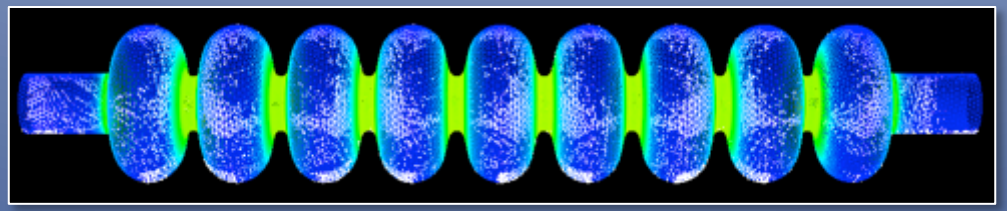
LCLS-II Design and Performance

P. Emma

…with input from many others

***LCLS-II* Instruments Workshop**

Oct. 5, 2016, ***SLAC***

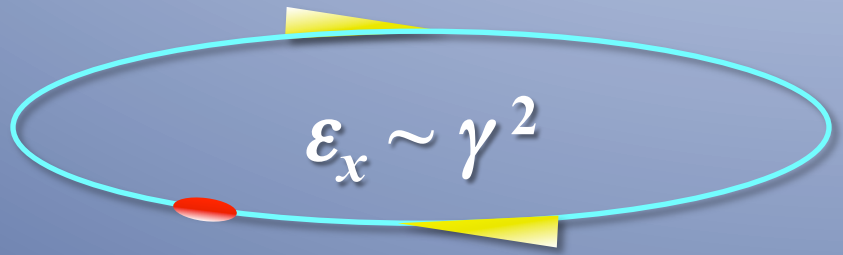


Outline of Presentation

- *LCLS-II* Introduction
- Accelerator and FEL Performance
  - New high-power SCRF linac (4 GeV, 0.2-5 keV)
  - Existing 1-km copper linac (3-15 GeV, 1-25 keV)
  - 2 new FEL undulators (adjustable gap)
- Operating Modes
- Future Options
- Time-Line

Why a Linear Accelerator?

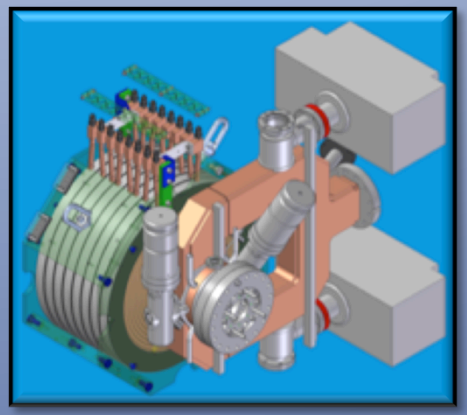
Storage ring…



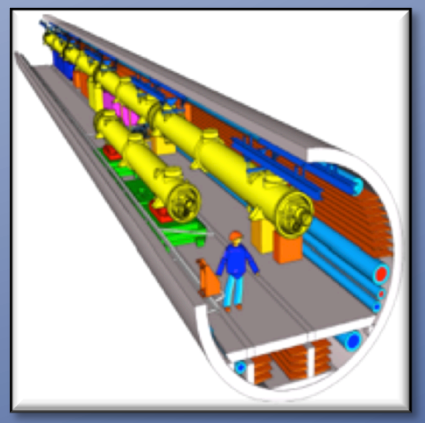
- Higher energy means larger emittance ☹
- Longitudinal emittance, $\gamma\varepsilon_z$, is **much** too large!

$\sigma_z \approx 5$ mm,
$\sigma_E/E \approx 0.1\%$ (1 GeV),
$\gamma\varepsilon_z = \sigma_z\sigma_E/mc^2 \approx$ **10000 μm**

RF Photocathode Gun (or DC gun)



Linac



$\varepsilon_x \sim 1/\gamma$

- Much smaller $\gamma\varepsilon_z$

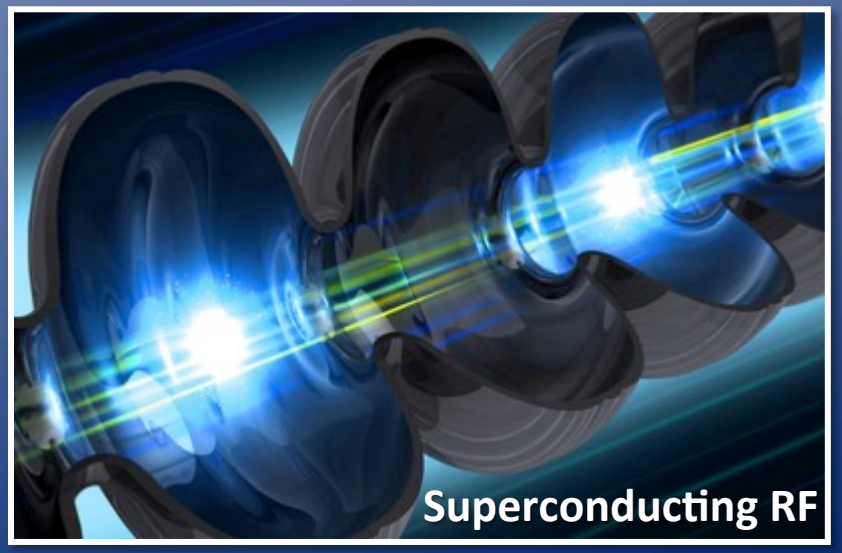
$\sigma_z \approx 1$ mm,
$\sigma_E/E \approx 0.05\%$ (5 MeV),
$\gamma\varepsilon_z = \sigma_z\sigma_E/mc^2 \approx$ **5 μm**

- Emittance scaling ($1/\gamma$)!

In terms of linear accelerators, SLAC will have both kinds (*Country* and *Western*)

- Existing **Cu-Linac** allows high e^- energy (**15 GeV**), but with pulsed RF (< 0.1% RF duty factor, **120 Hz** beam rate)

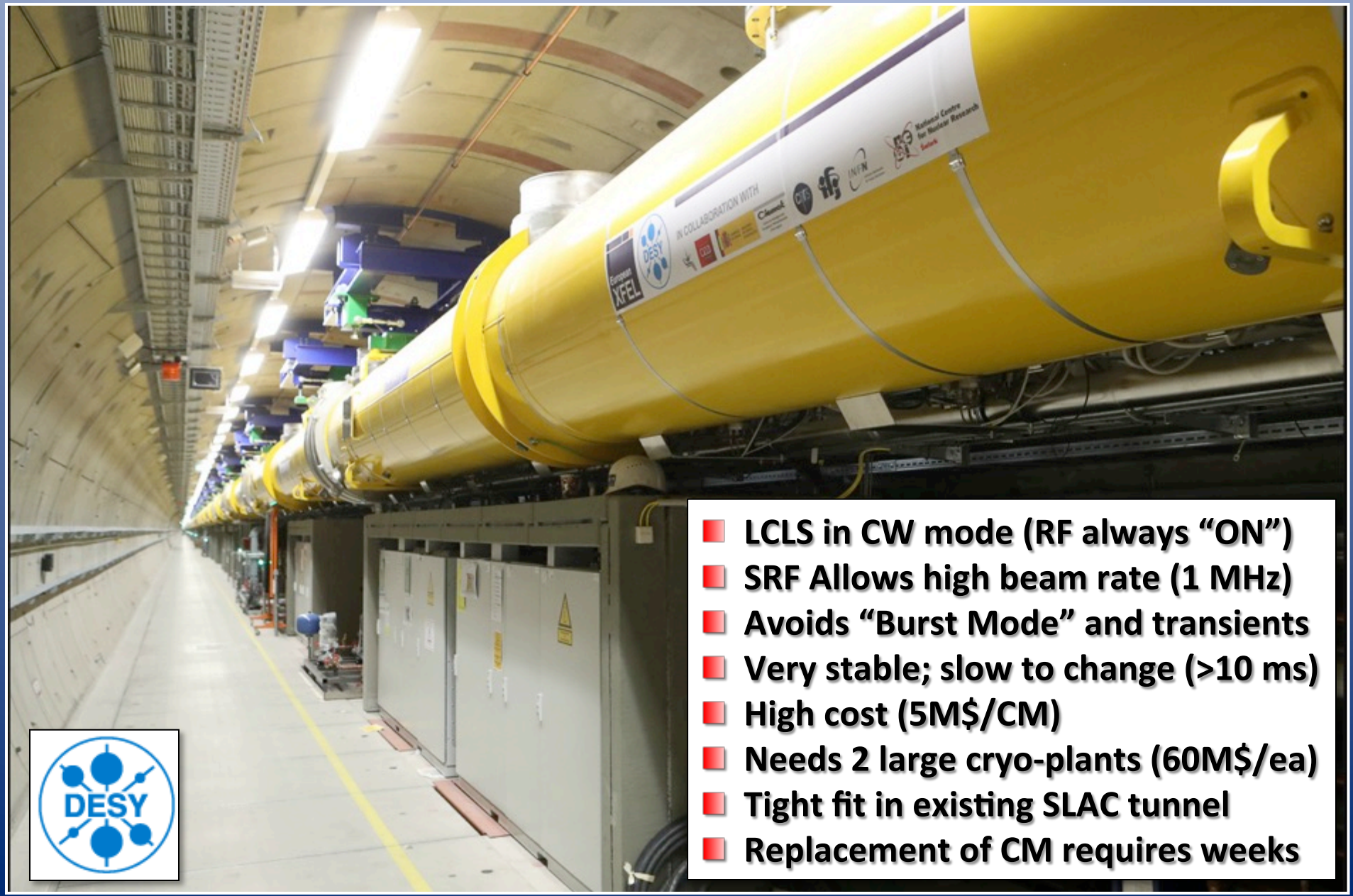
- New **SCRF-Linac** allows high rate (**1 MHz**), but low e^- energy (**4 GeV**) using **CW** RF



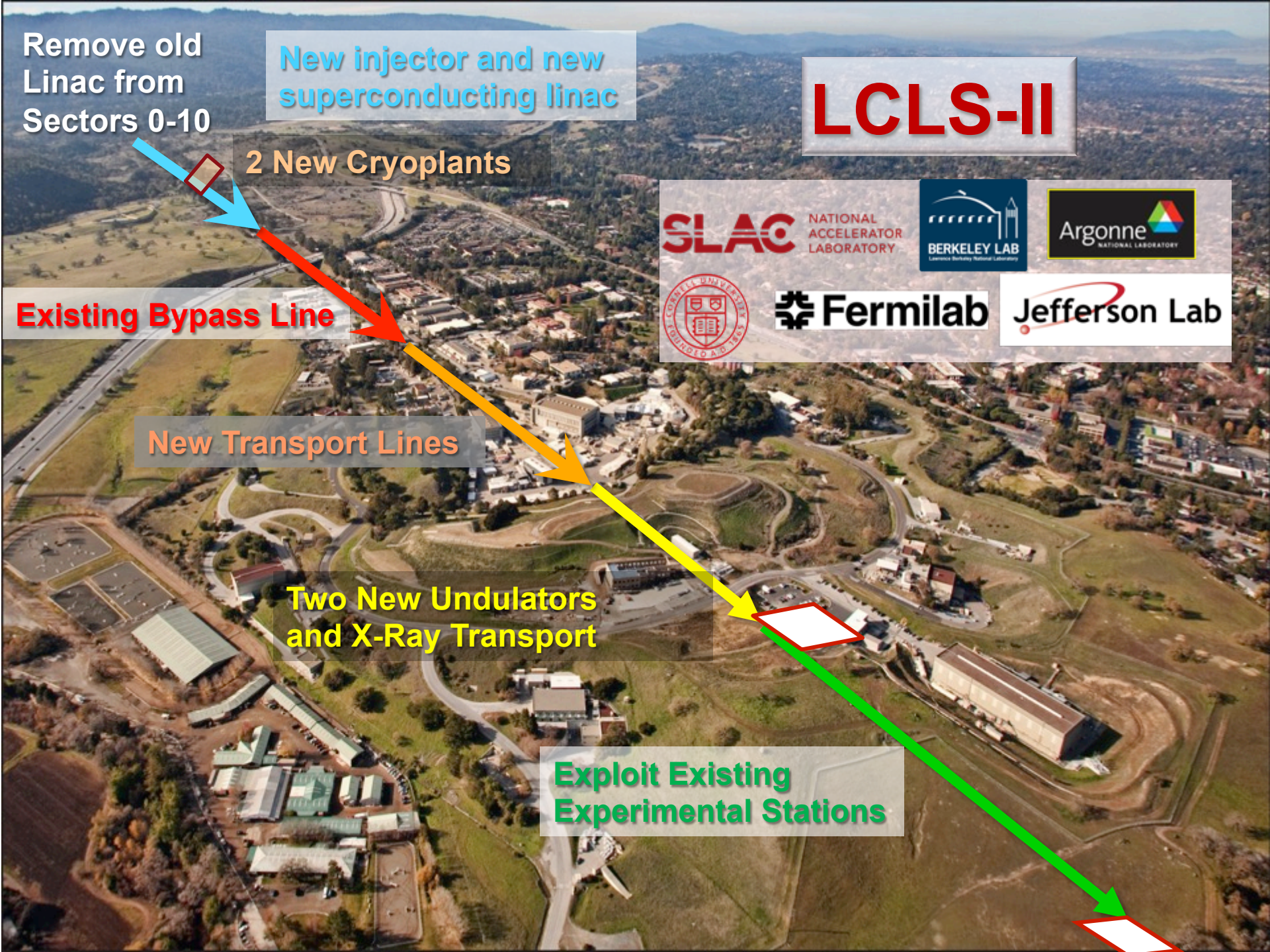
***LCLS-II* will have both!**

(smooth x-ray delivery)

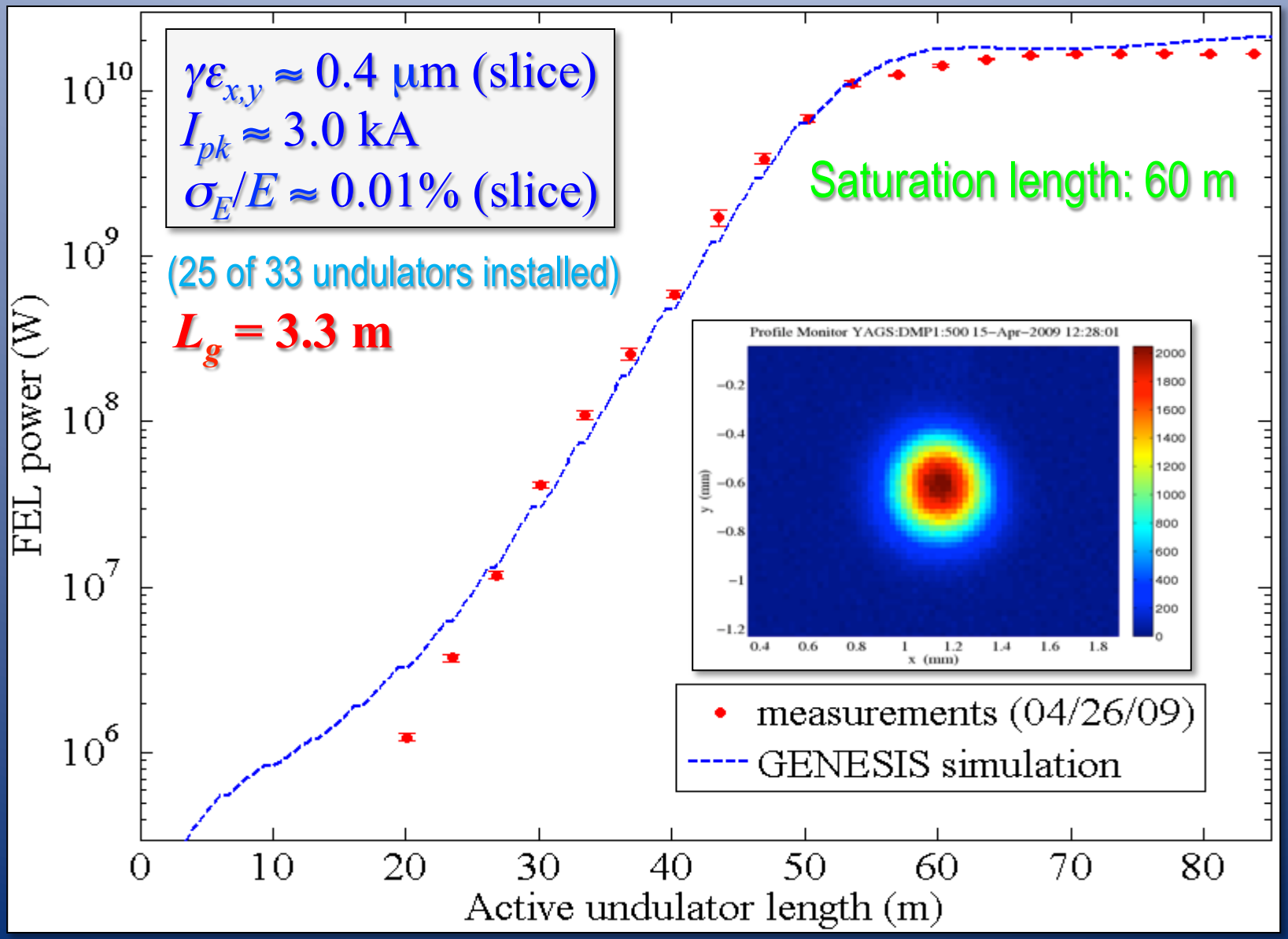
Superconducting RF Based on XFEL (*DESY*)



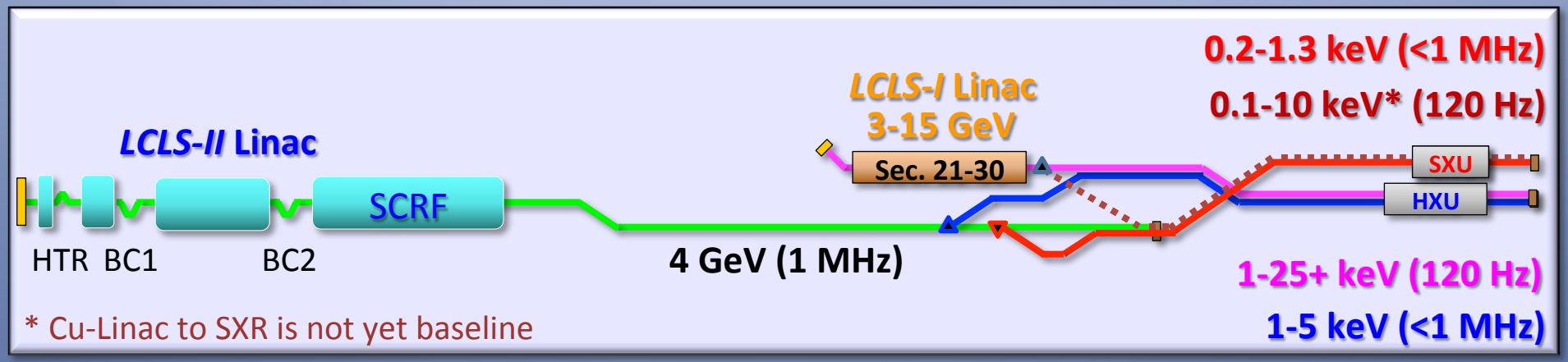
- LCLS in CW mode (RF always "ON")
- SRF Allows high beam rate (1 MHz)
- Avoids "Burst Mode" and transients
- Very stable; slow to change (>10 ms)
- High cost (5M$/CM)
- Needs 2 large cryo-plants (60M$/ea)
- Tight fit in existing SLAC tunnel
- Replacement of CM requires weeks

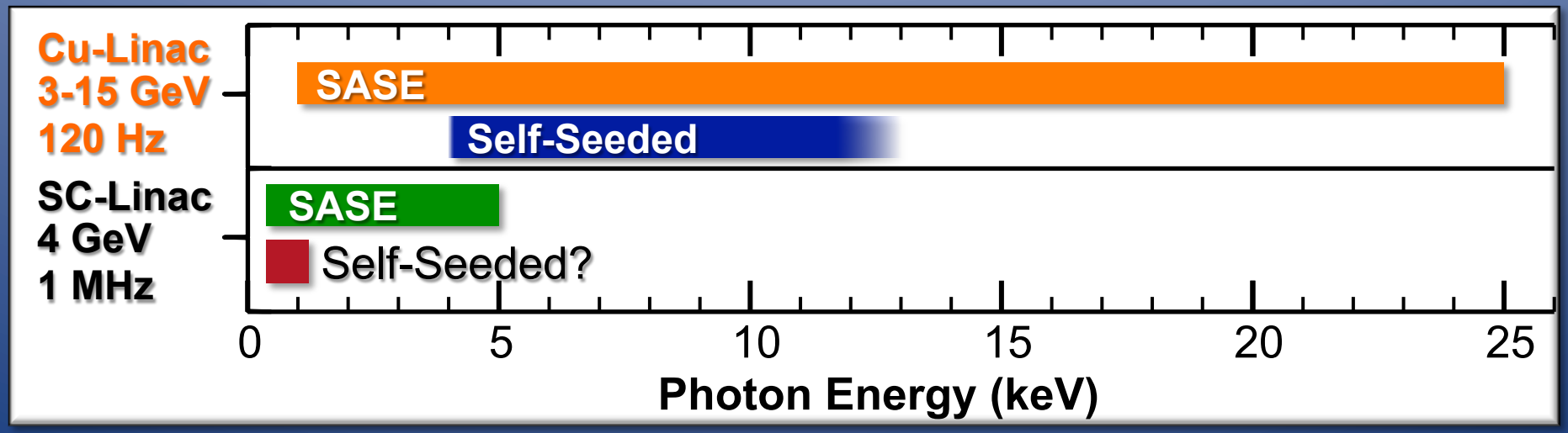

Remove old Linac from Sectors 0-10
New injector and new superconducting linac
LCLS-II
2 New Cryoplants
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Fermilab
Jefferson Lab
Existing Bypass Line
New Transport Lines
Two New Undulators and X-Ray Transport
Exploit Existing Experimental Stations

LCLS-I FEL Lasing at 1.5 Å (April 2009)



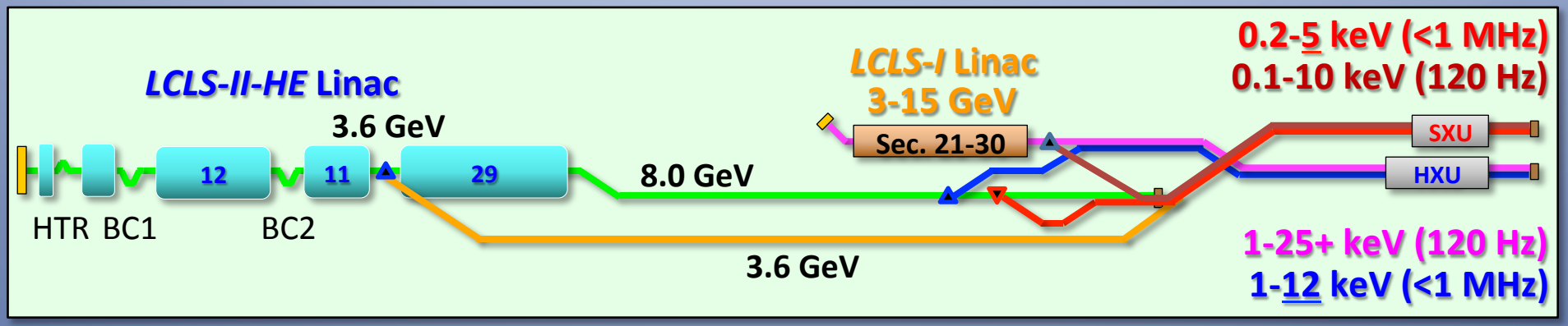
LCLS-II Layout and Performance





- Each main electron beam dump is rated for < 120 kW of average beam power
- Beam rate must be reduced when bunch charge is increased
- For example: 100 pC at 300 kHz, or 30 pC at 1 MHz (4 GeV)

LCLS-II-HE → Upgrade to 8 GeV

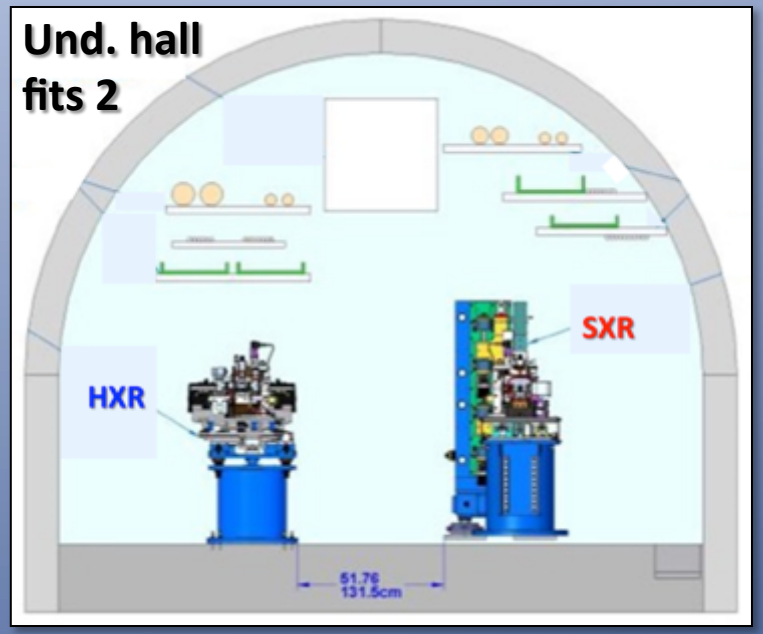


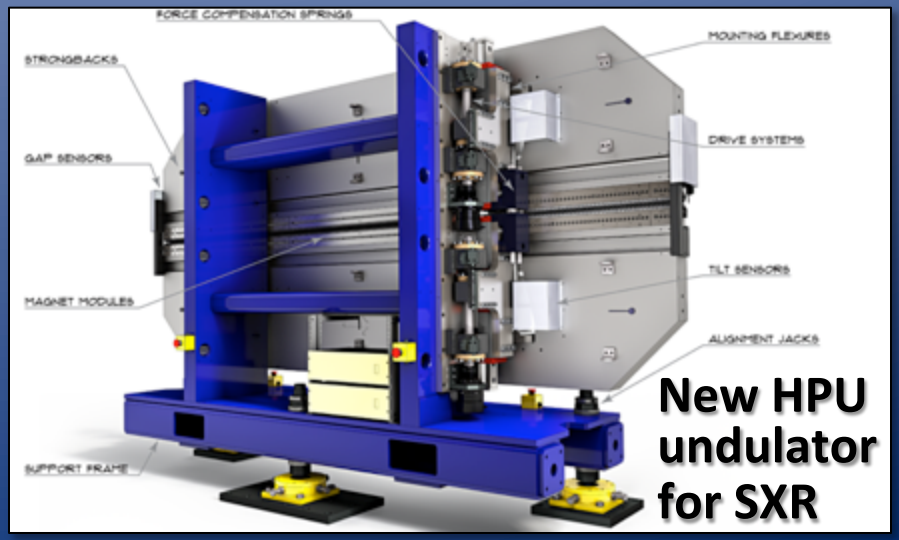
- Add **20** new cryomodules (35 → **55**)
- More RF gradient (16 → **19.6** MV/m)
- **8-GeV** SCRF linac to feed SXR or HXR
- **3.6-GeV** fast kicker take-off to SXR
- Allows **6** different operating modes

FNAL

SXR options	HXR options-1	or	HXR options-2
3-3.6 GeV SC-Linac (< 1 MHz) **0.1-1.3 keV** with > 20 W	4-8 GeV SC-Linac (< 1 MHz) **1-13 keV** with > 20 W	or	3-15 GeV Cu-Linac (≤ 120 Hz) **1-25 keV** with mJ pulses
4-8 GeV SC-Linac (< 1 MHz) **0.2-13 keV** with > 20 W	4-8 GeV (tied to SXR) SC-Linac (< 1 MHz) **1-13 keV** with > 20 W	or	3-15 GeV Cu-Linac (≤ 120 Hz) **1-25 keV** with mJ pulses
3-10 GeV Cu-Linac (≤ 120 Hz) **0.1-10 keV** with mJ pulses	4-8 GeV SC-Linac (< 1 MHz) **1-13 keV** with > 20 W	or	3-15 GeV (tied to SXR) Cu-Linac (≤ 120 Hz) **1-25 keV** with mJ pulses

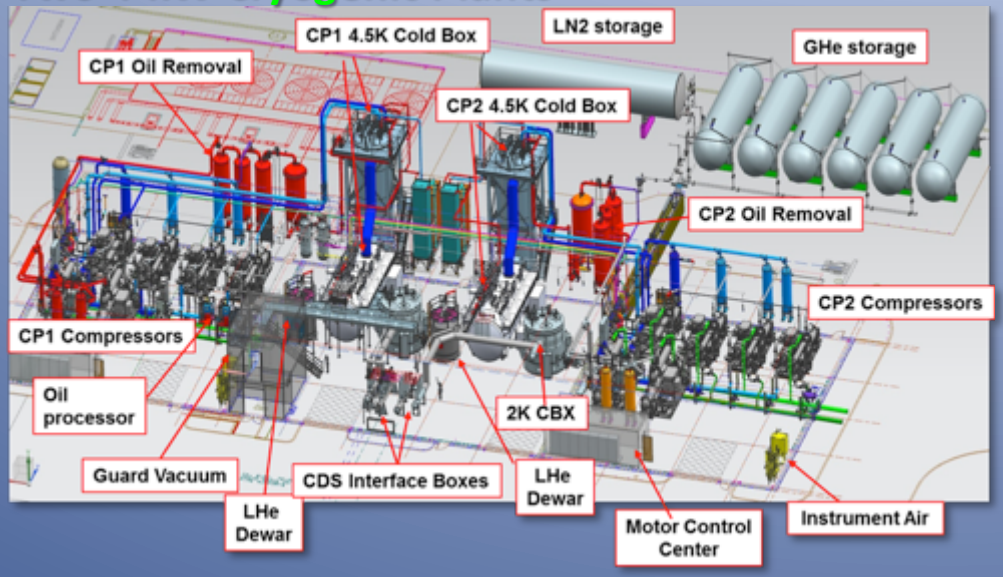
Undulator hall will be filled with 2 new undulators

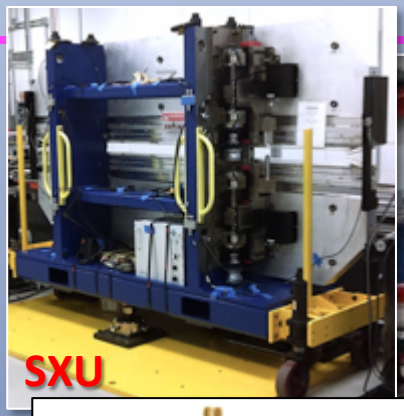


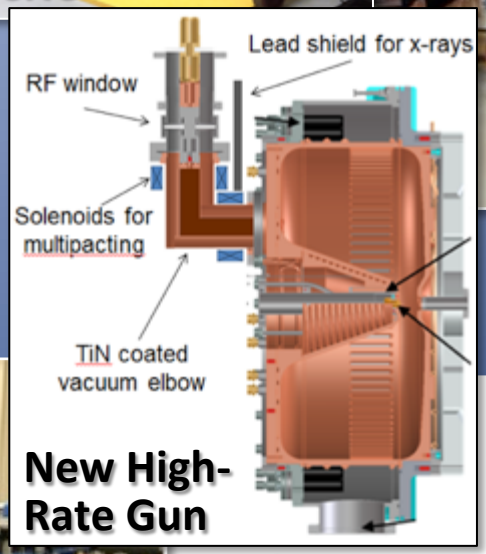


Many New Components and Systems

Two 4-kW Cryogenic Plants





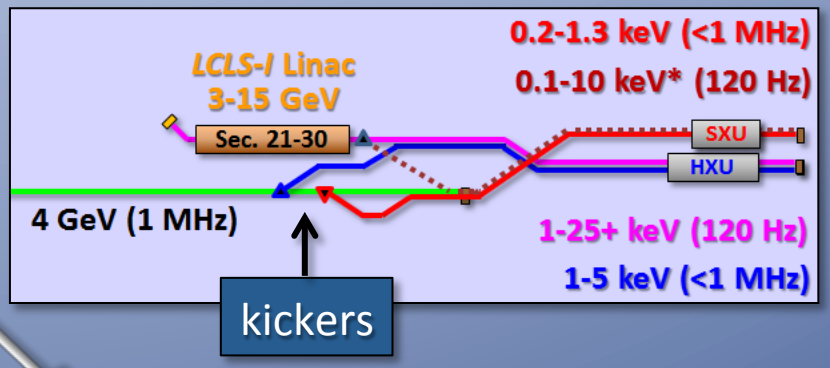


FEL tuning range & response times for users

Color Code: SC-Linac & Cu-Linac

Photon Energy (0.2-5 keV & 1-25 keV)

- ±1% is fast using e^- energy (10 ms)
- Full range uses gap control (5 min.)
- Cu-Linac slow if $|\Delta\lambda/\lambda|$ > 10% (15-30 min)
- Use e^- energy or gap (3-15 GeV)



Pulse Duration

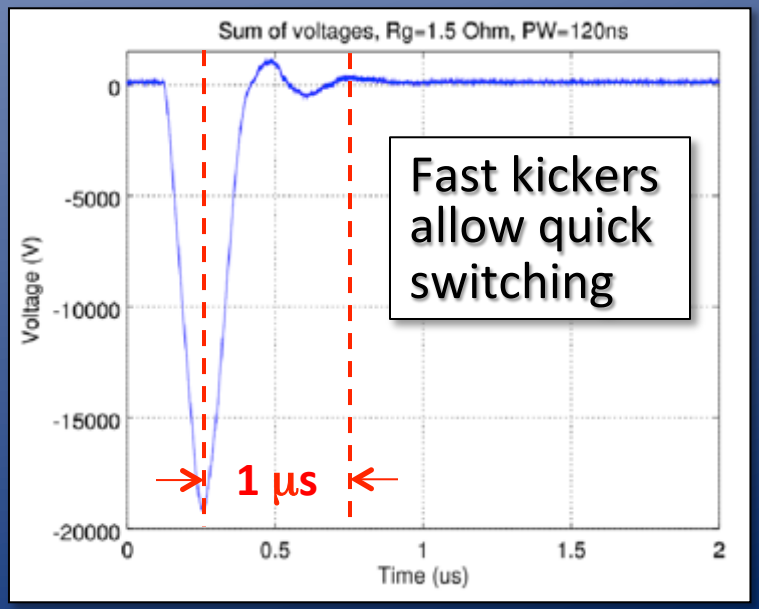
- 20-300 fs (slow changes: 1-2 hrs)
- Use of slotted-foil may limit beam rate
- Cu-Linac as now (1-min, 50-500 fs, SXR's)
- < 10 fs with low bunch charge (1 hr)

Beam Rates (< 1 MHz & 120 Hz)

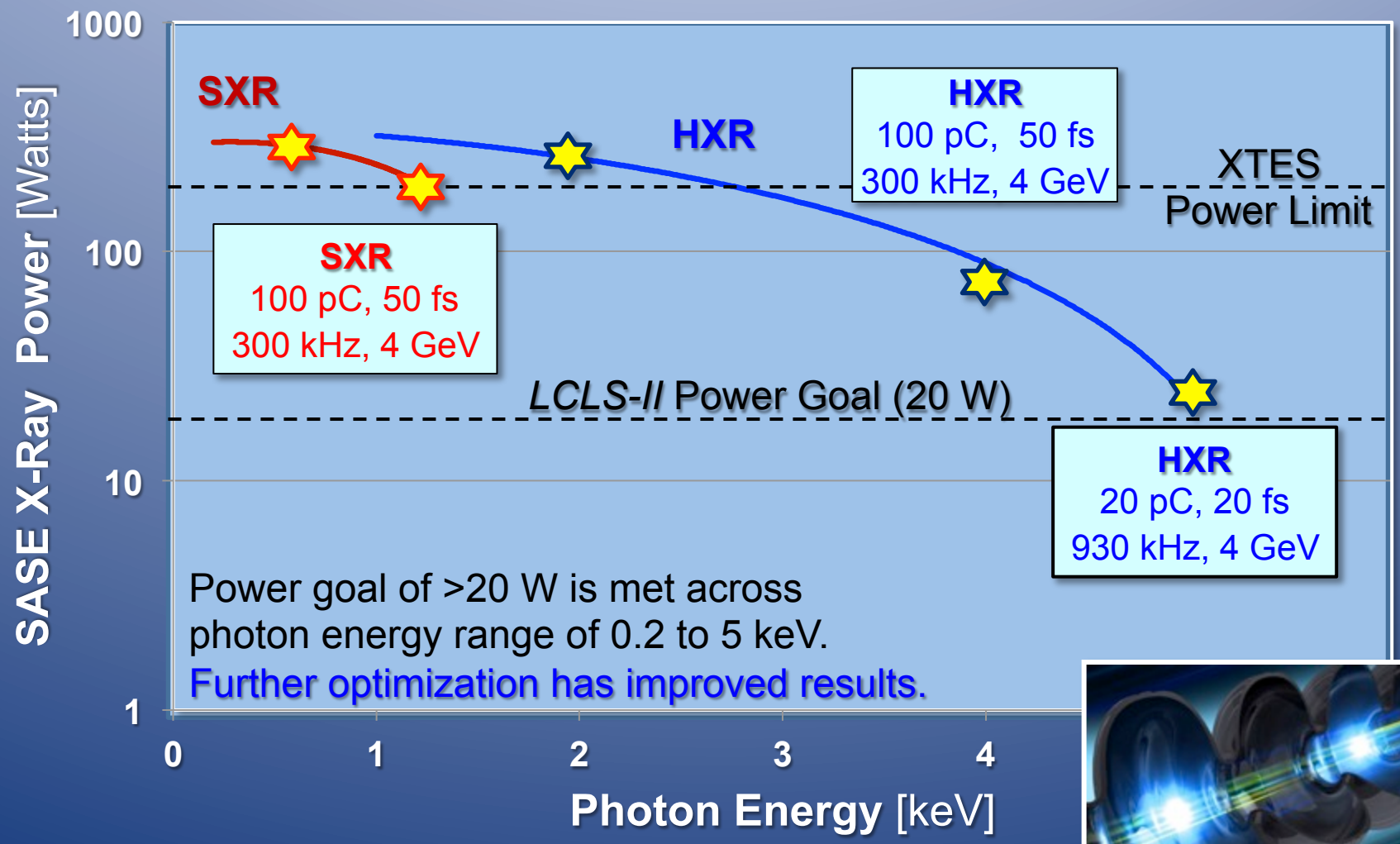
- Trigger fast kickers (μsec or slower)
- Choose from 'one-shot' to 1 MHz
- Total beam power/FEL < 120 kW (rate limit)

X-Ray Pulse Energy

- Up to 8 mJ (250-fs pulse, 250 eV, → 800 W)
- 3-6 mJ (highest at 3-6 keV)



SC-Linac → SXR & HXR FEL Performance Simulations



= Tracking results (SXR, HXR)

...as driven by SC-Linac

G. Marcus

SC-Linac → HXR & SXR FEL Performance Simulations

Q (pC)	E_γ (keV)	f (MHz)	E (μJ)	Δt_{FW} (fs)	ΔE_γ (eV)	P_{pk} (GW)	P_{avg} (W)
20	0.25	1.0	390	46	2.6	8.0	393
	0.75	1.0	270	35	2.1	7.5	266
	1.25	1.0	220	35	2.2	6.3	222
100	0.25	0.3	2550	120	0.91	21	765
	0.75	0.3	1640	110	2.4	14	490
	1.25	0.3	1010	108	3.3	9.2	302
300	0.25	0.1	8800	250	1.0	34	880
	0.75	0.1	5700	234	2.1	24	570
	1.25	0.1	3390	223	2.7	15	339

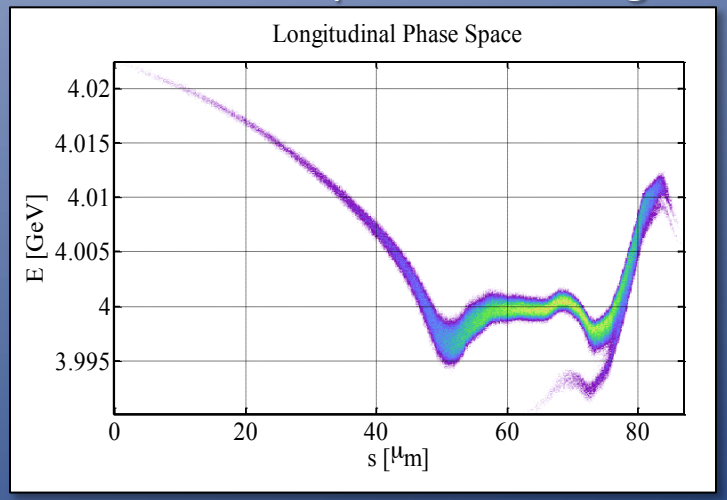
SXR

Q (pC)	E_γ (keV)	f (MHz)	E (μJ)	Δt_{FW} (fs)	ΔE_γ (eV)	P_{pk} (GW)	P_{avg} (W)
20	1.5	1.0	250	30	3.3	7.8	250
	3.25	1.0	190	30	5.3	6.2	190
	5.0	1.0	37	28	4.3	1.3	37
100	1.5	0.3	1730	108	3.9	16	519
	3.25	0.3	620	104	5.8	5.9	185
	5.0	0.3	6	60	2.0	0.075	1.8
300	1.5	0.1	4570	215	3.9	21	457
	3.25	0.1	2060	206	8.1	9.9	206
	5.0	0.1	-	-	-	-	-

HXR

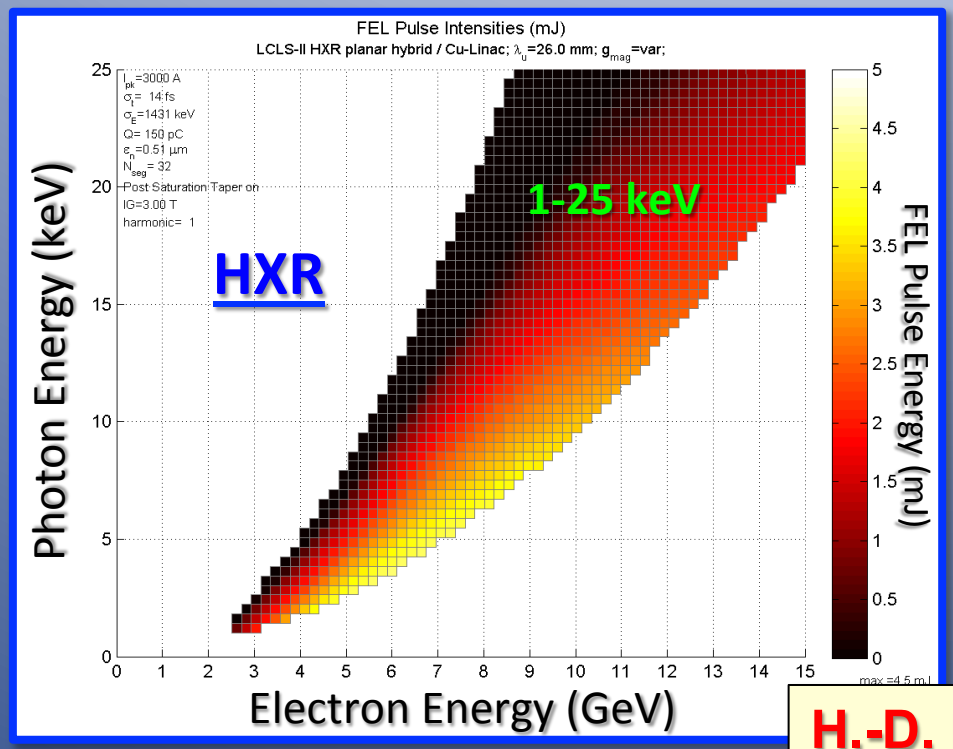
...as driven by SC-Linac

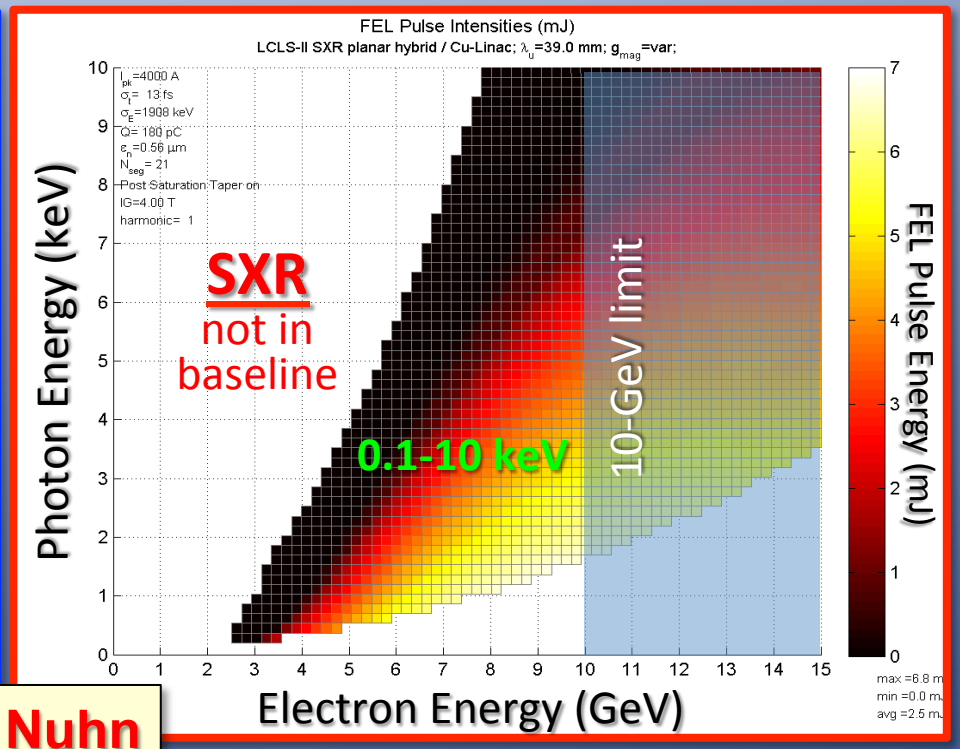
Detailed particle tracking



G. Marcus, *et al.*

Cu-Linac → HXR & SXR FEL Performance Simulations

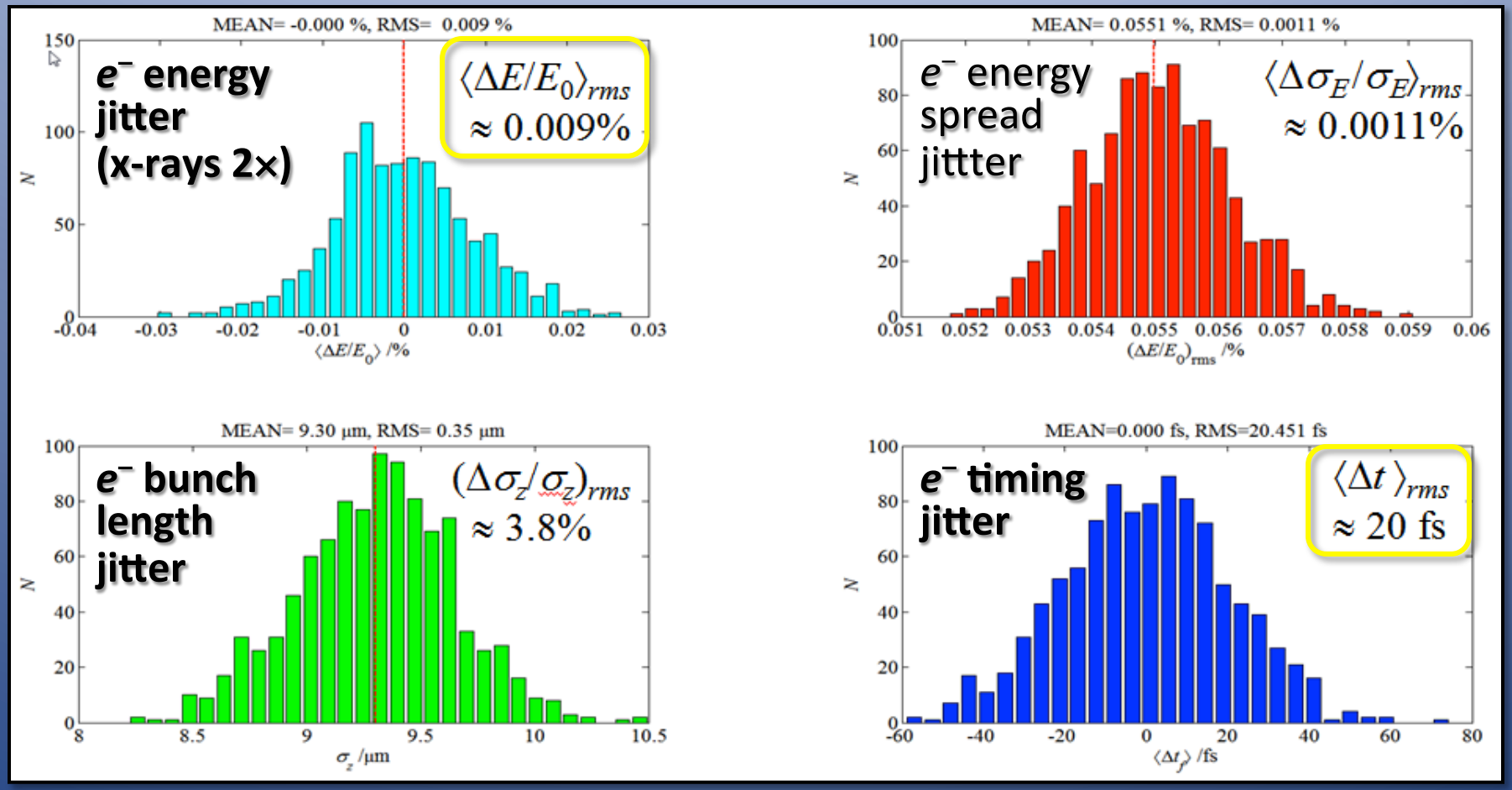




H.-D. Nuhn

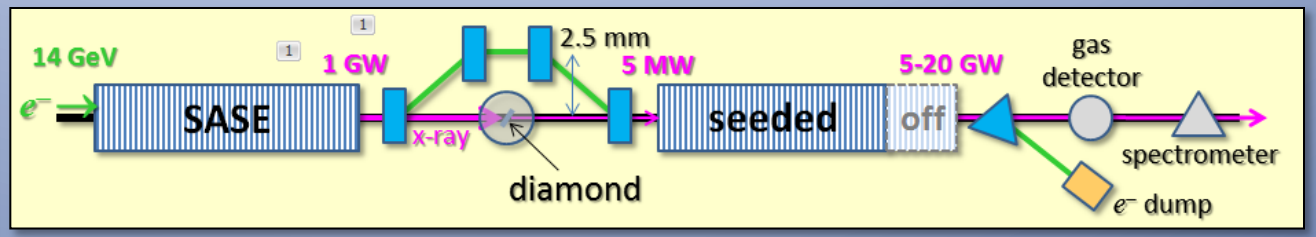
...as driven by Cu-Linac (120 Hz)

e^- Stability Expectations (conservative)

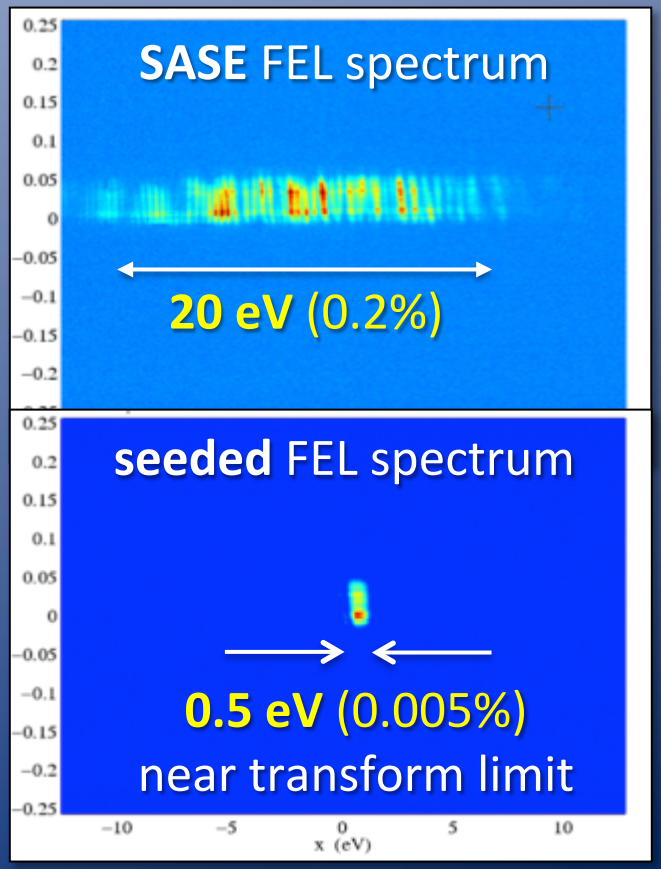


- Shows estimated *pulse-to-pulse* jitter (rms)
- Slow drift will be removed with beam-based feedback (as at *LCLS-I*)
- Actual jitter may be even less (3-5 times) than shown
- Should be considerably better than *LCLS-I*

Self-Seeding at *LCLS-II*

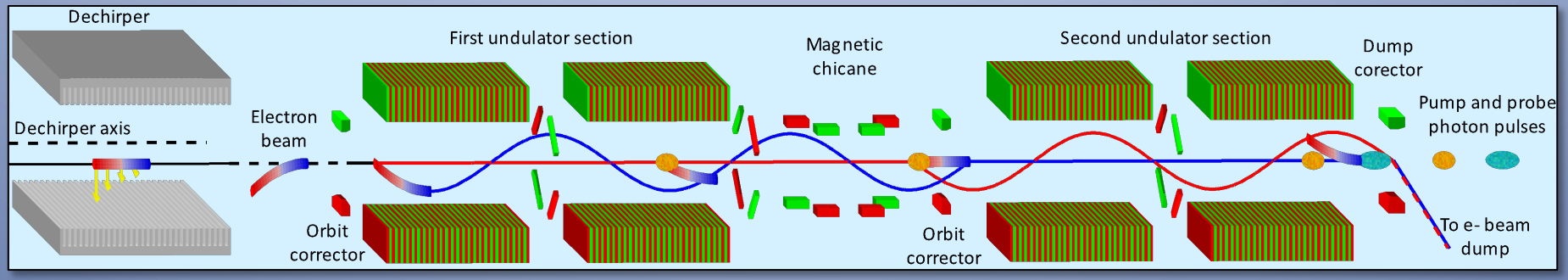


demonstrated at ***LCLS***, ***Nature Photonics 6,*** *693-698 (2012).*



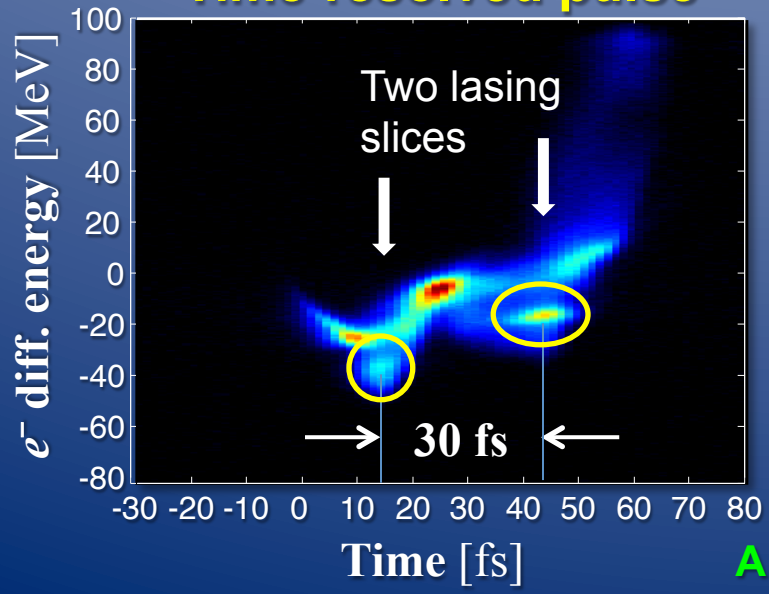
- **Hard X-Ray self-seeding will be possible, as it is now (low rate, Cu-Linac, 4-12 keV).**
- **Crystal will be rotated as optimal for vertical polarization.**
- **Soft X-Ray self-seeding has been de-scoped from the project** (*LCLS* directorate).

Two-Color Possibilities at *LCLS-II*

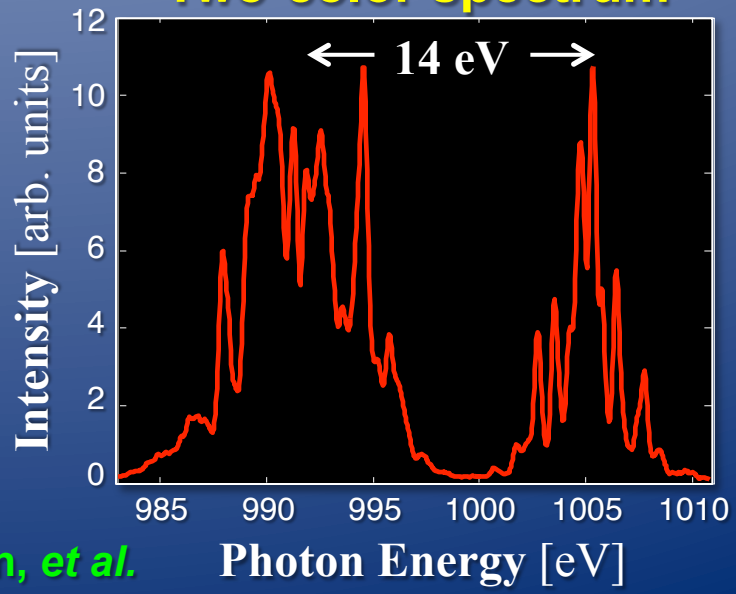


- Fresh-bunch lasing of two slices at different times/energies
- 2-color, time-delayed X-ray pulses for pump-probe studies with up to 1 mJ/pulse (−15 to 950 fs) – "Dechirper" not in baseline

Time-resolved pulse



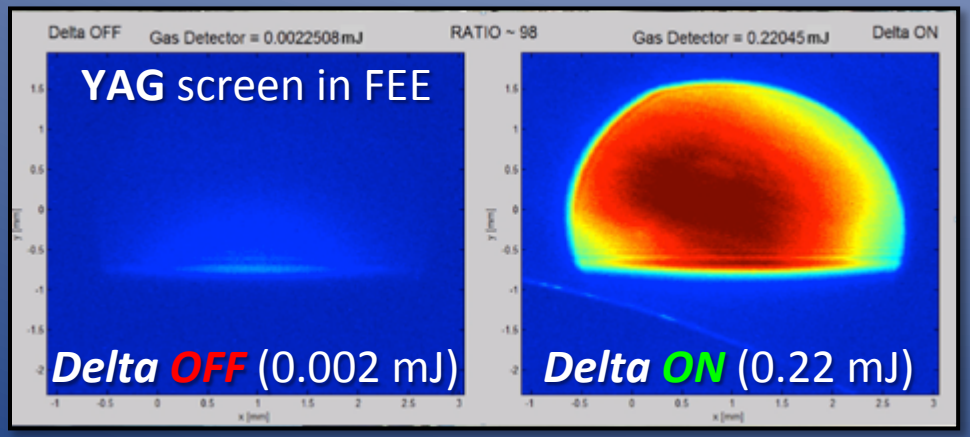
Two-color spectrum



A. Lutman, *et al.*

Polarization Control at *LCLS-II SXR* (future)

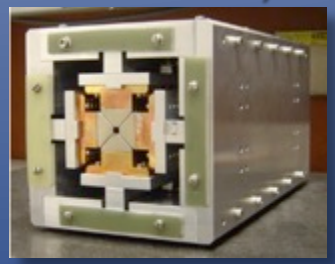
- *Delta-I* is operational
- *Delta-II* for SXR: larger *K* & var. gap
- Add three 3.3-m long *Delta-II*'s at end of SXR und. (not in *LCLS-II* baseline)
- Simulations: 5-7 GW (w/3 *Delta-II*'s)
- 100% polarization (goal <1% stability)
- All orientations possible (planar: *x* or *y*; circular: *L* or *R*) – change in ~1 min.



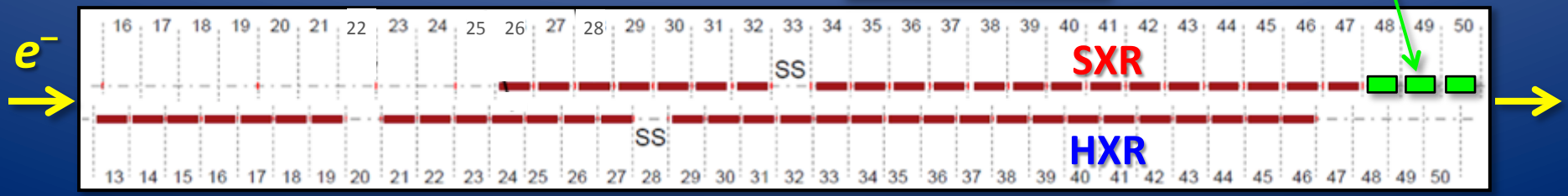
nature photonics ARTICLES
PUBLISHED ONLINE: 9 MAY 2016 | DOI: 10.1038/NPHOTON.2016.79

Polarization control in an X-ray free-electron laser

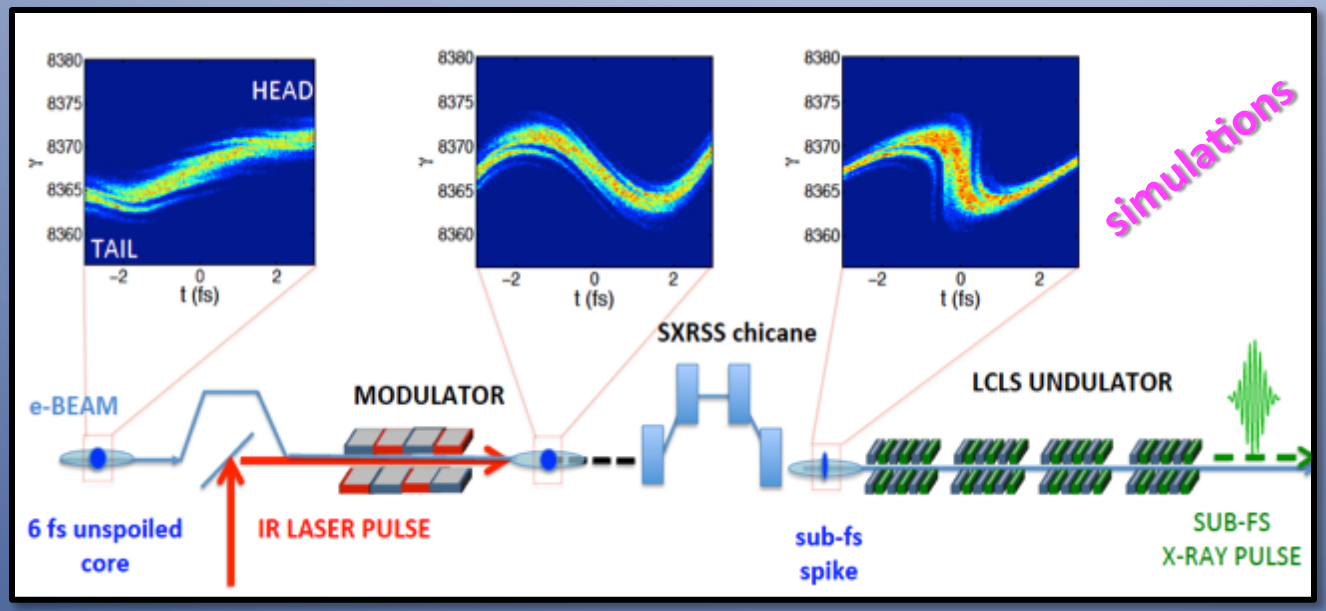
A. Lutman, H.-D. Nuhn, F. Peters, *et al.*



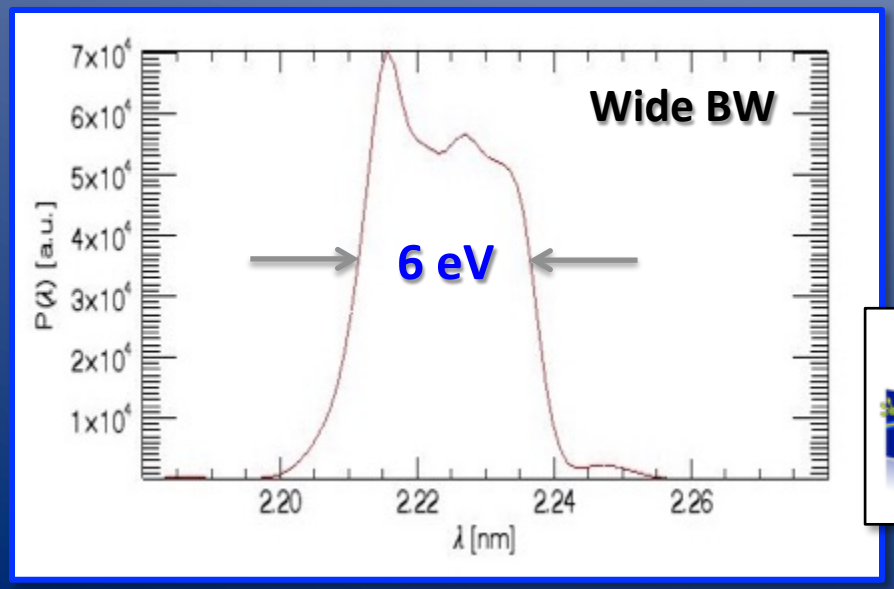
3 new *Delta-II*'s

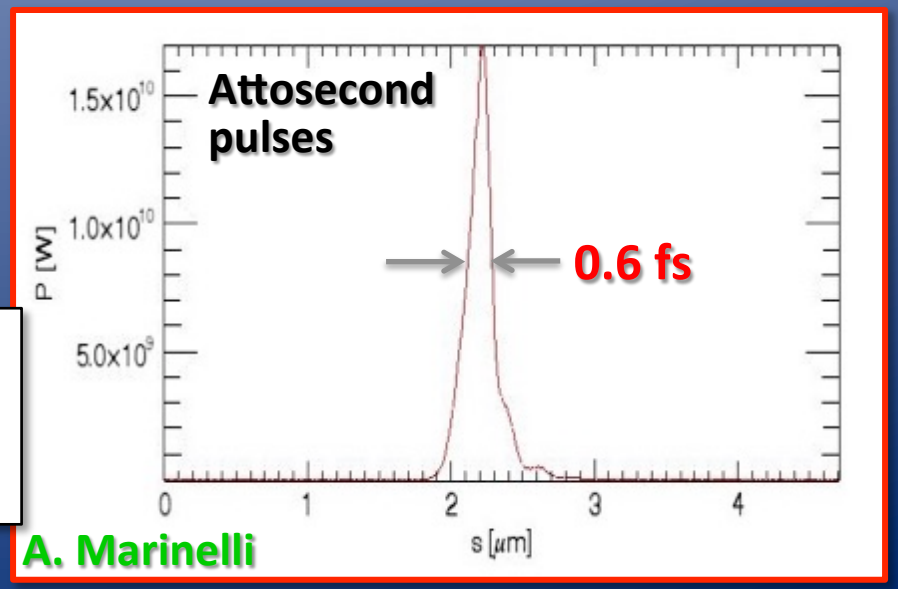


Attosecond Pulses - XLEAP & XLEAP-II

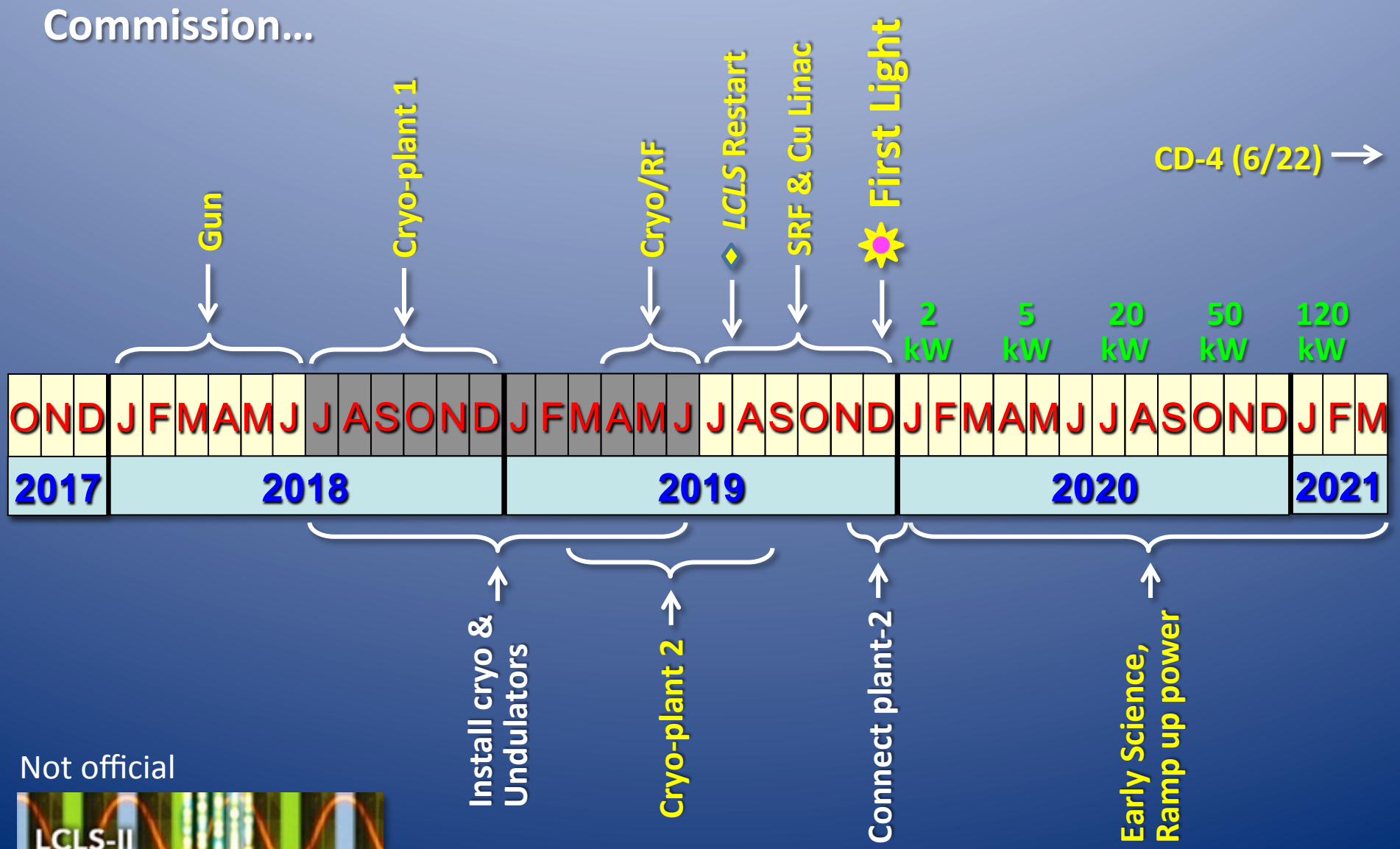


- < 1 fs pulse duration
- Multi-eV BW
- 20-μJ pulse energy
- 1 or 2-color operation with sub-fs jitter
- ≤ 1 kHz w/exist. Laser
- Upgrade to 100 kHz with high-average power OPCPA
- Results in late 2017





LCLS-II Time Line



Not official

Summary

- *LCLS-II* will be a highly flexible machine with…
  - Two separate linear accelerators (CuRF & SCRF)
  - Two separate FEL undulators (variable gap)
  - High-rate beam delivery at 0.2-5 keV (upgrade to 13 keV)
  - High-energy, low-rate beam delivery at 1-25 keV
  - Variable wavelength, pulse duration, power, and rate
  - Improved stability over *LCLS-I* (energy, power, timing)
  - Self-seeding, two-color, polarization, & attosecond options
- Average x-ray power (SCRF) may approach 1 kW
- Upgrade paths (8 GeV, SXRSS, SC-undulators, $\gamma\varepsilon \downarrow$)
- "First Light" is scheduled for start of FY-2020

SLAC NATIONAL ACCELERATOR LABORATORY

End

Key Performance Parameters (KPP's) for *LCLS-II*

- Build new 4-GeV superconducting RF linac in 1st km of SLAC tunnel
- New linac beam rate is up to 1 MHz with CW RF
- Exiting LCLS-I retains performance (gets new adjustable undulator)
- Beam to be fast switched between either of 2 new undulators

Performance Measure	Threshold	Objective
Variable Gap Undulators	2 (SXR & HXR)	2 (SXR & HXR)
Super Conducting Linac Based FEL System		
Super Conducting Linac Energy	3.5 GeV	$\geq$ 4 GeV
Electron Bunch Repetition Rate	93 kHz	929 kHz
Super Conducting Linac Charge per Bunch	0.02 nC	0.1 nC
Photon Beam Energy Range	250-3,800 eV	200-5,000 eV
High Repetition Rate Capable End Stations	$\geq$ 1	$\geq$ 2
FEL Average Power (10^-3 BW)	5×10^8 (10x spontaneous @2,500 eV)	$>10^{11}$ @ 3,800 eV
Normal Conducting Linac Based FEL System		
Normal Conducting Linac Electron Beam Energy	13.6 GeV	15 GeV
Electron Bunch Repetition Rate	120 Hz	120 Hz
Normal Conducting Linac Charge per Bunch	0.1 nC	0.25 nC
Photon Beam Energy Range	1,000-15,000 eV	1,000-25,000 eV
Low Repetition Rate Capable End Stations	$\geq$ 2	$\geq$ 3
FEL Photon Energy (10^{-3} BW[a])	10^{10} (lasing @ 15,000 eV)	$> 10^{12}$ @ 15,000 eV

Electron Parameters for SCRF Linac

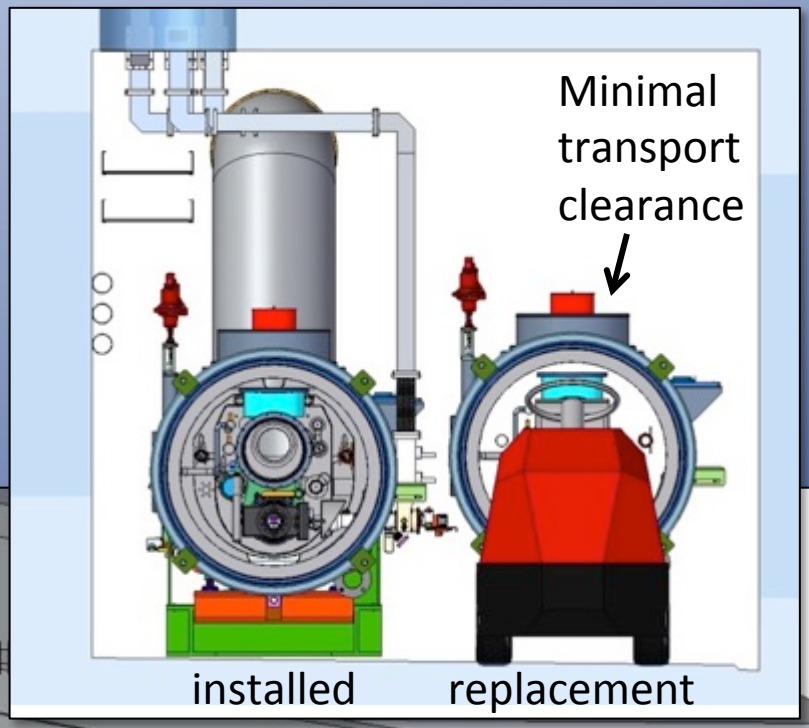
Parameter (SCRF Linac)	symbol	nominal	range	units
Electron Energy	E_f	**4.0**	2.0 - 4.5	GeV
Bunch Charge	Q_b	**100**	10 - 300	pC
Bunch Repetition Rate in Linac	f_b	**0.62**	0 - 0.93	MHz
Average e^- current in linac	I_{avg}	**0.062**	0.0 - 0.3	mA
Avg. e^- beam power at linac end	P_{av}	**0.25**	0 - 1.2	MW
Norm. rms slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	**0.45**	0.2 - 0.7	μm
Final peak current (at undulator)	I_{pk}	**1000**	500 - 1500	A
Final slice E-spread (rms, w/heater)	σ_{Es}	**500**	125 - 1500	keV
X-ray pulse duration (FWHM)	$\Delta\tau_{FW}$	**100**	20 - 300	fs

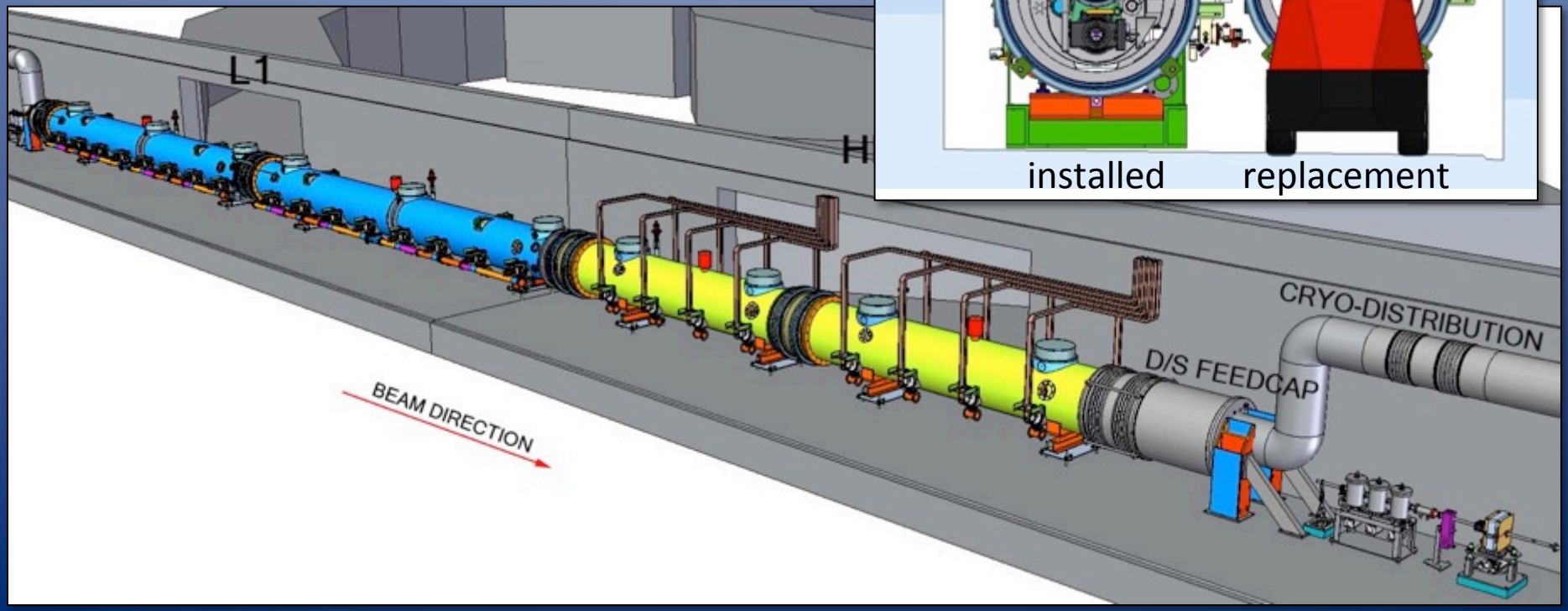
New challenges:

- CW superconducting RF system
- High brightness CW injector
- Two variable gap undulators (both new)
- Very high beam power
- Beam dynamics of high brightness electron beams

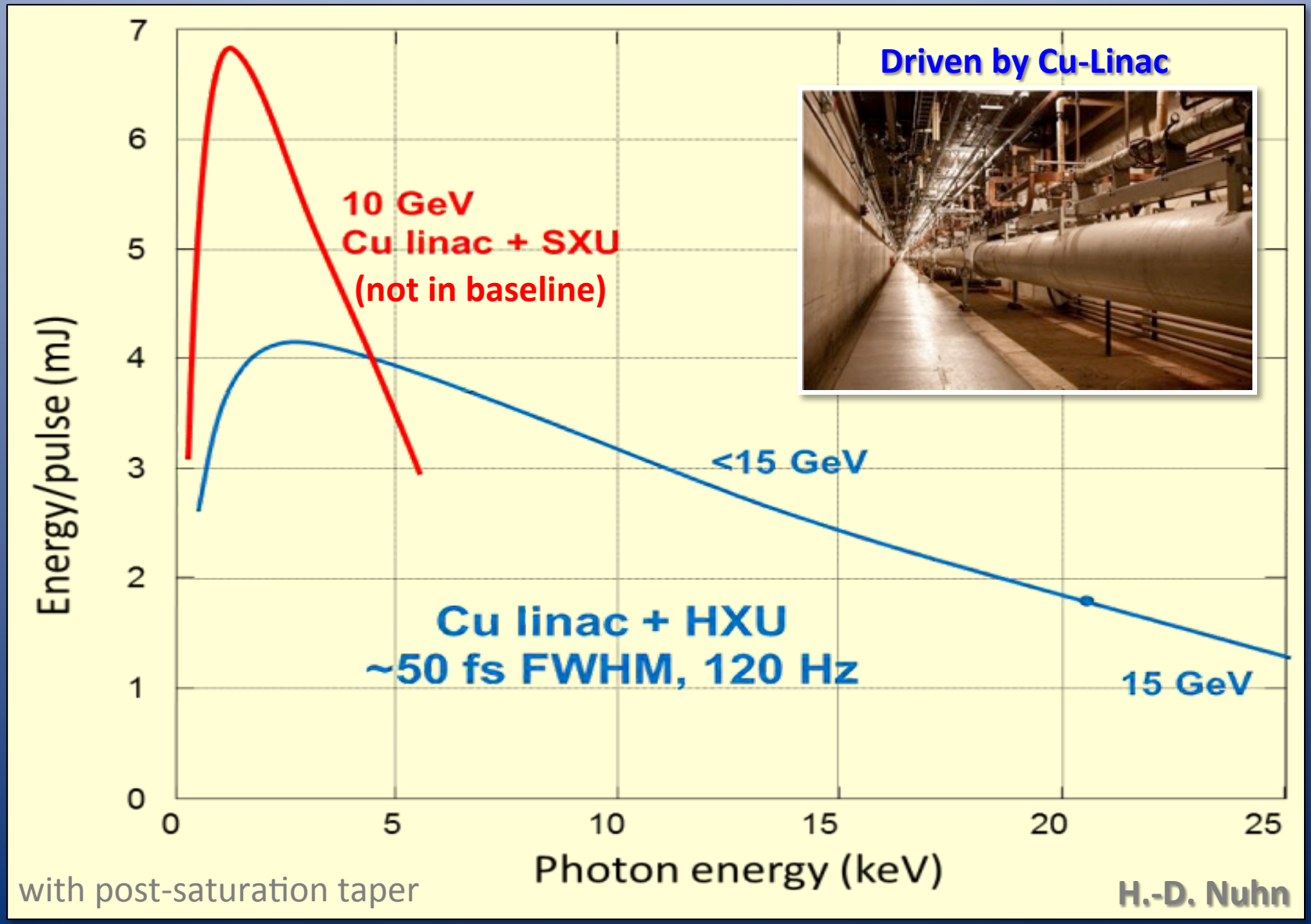
SLAC Tunnel will House 2 Linacs

- Remove old Cu-Linac in 1st km
- Install 35 12-m long cryomodules
- Replacements barely clear

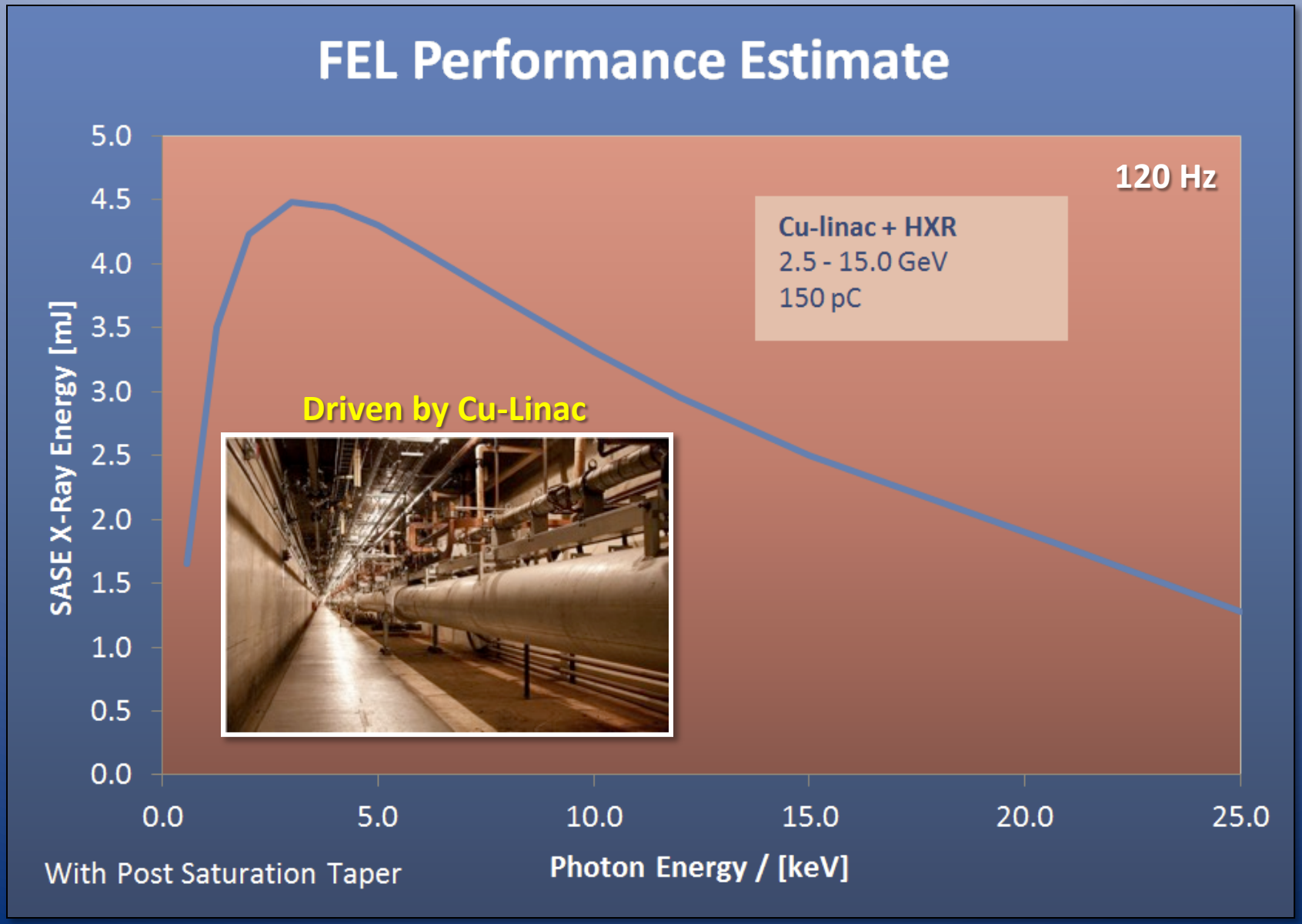




Cu-Linac → HXR & SXR FEL Performance Simulations



CuRF FEL Performance Simulations



LCLS-II relative to normal conducting LCLS-I

Pro's

- Four orders of magnitude increase in beam power and efficiency relative to LCLS-I
- Can vary the bunch spacing (users generally want > 1 us)
- Better beam energy stability due to continuous feedback
- Cavities operate with only a few kWs of input RF power vs MWs

Con's

- Large cryoplant required (20 % of the cost), difficult to operate
- Cavity performance very sensitive to cleanliness – requires clean room techniques
- Cavity bandwidth very narrow – non-trivial to stabilize gradient
- Linac basically inside a vacuum vessel – design, assembly and repairs are challenging

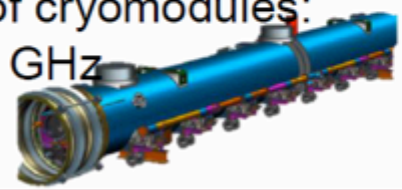
Project Collaboration

Project Collaboration

SLAC

Fermilab

½ of cryomodules: 1.3 GHz



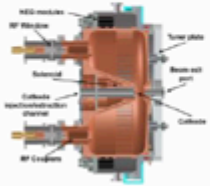
Jefferson Lab
EXPLORING THE NATURE OF MATTER

½ of cryomodules: 1.3 GHz

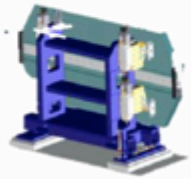
Cryoplant

Berkeley Lab

e^- gun & associated injector systems



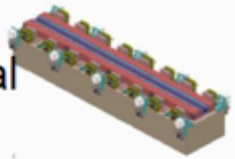
Undulators



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