Instrumentation and Diagnostics for High Repetition Rate Linac-driven FEL

J. Byrd, J. Corlett, S. De Santis, L. Doolittle, P. Emma D. Filippetto, G. Huang, M. Placidi, A. Ratti.

Lawrence Berkeley National Laboratory

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What's So Special About High Repetition Rate ?

- Advantages from the beam diagnostics point of view:
  - *Averaging*
    - Accumulation of very low intensity data (ODR, low bunch charge, sliced measurements…)
    - Short averaging time
  - *Destructive measurements during user operations*
    - Pulse stealing
  - *Rep. rate in the same range of synchrotron ring*
    - Can use same instrumentation
  - *Fast feedback*
    - Higher sampling rate

…But There Is No Free Lunch

- Challenges from the beam diagnostics point of view:
  - *Beam Stability*
    - Level of beam stability achieved sets averaging limits
    - Faster beam-based feedback helps.
  - *High Total Beam Power*
    - Intercepting diagnostics can be damaged
  - *High Rep. Rate Always Comes With Short Bunches*
    - Elevated power level at higher frequencies (loss factor…)
    - Microbunching (COTR "blinding" effects)
  - High Frequency Synchronization
    - Beam timing monitor (few 10's fs resolution)

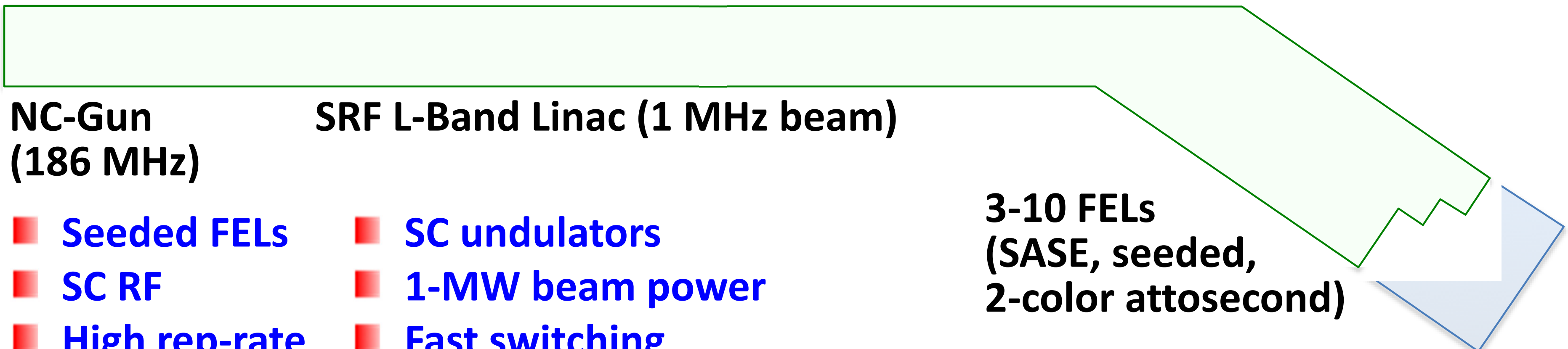
Comparison of Linac-based Light Sources

	LCLS	FERMI	NGLS	XFEL	ERL
Beam Energy (GeV)	4.3÷14.35	1.2÷1.7	2.4	17.5	5.3
Bunch Charge (pC)	1000	1000	30÷300	1000	77
Bunch Length (fs)	10's	500	<250	80	300
Beam Power (kW)	1.7	0.1	720	500 (80 MW peak)	530
Bunch Rep. Rate (Hz)	120	50	10^5 to 10^6	4.8×10^6	1.3×10^9

Buil up on the experience of existing, low-rep rate machines to develop the diagnostics for the real high-rep rate ones.

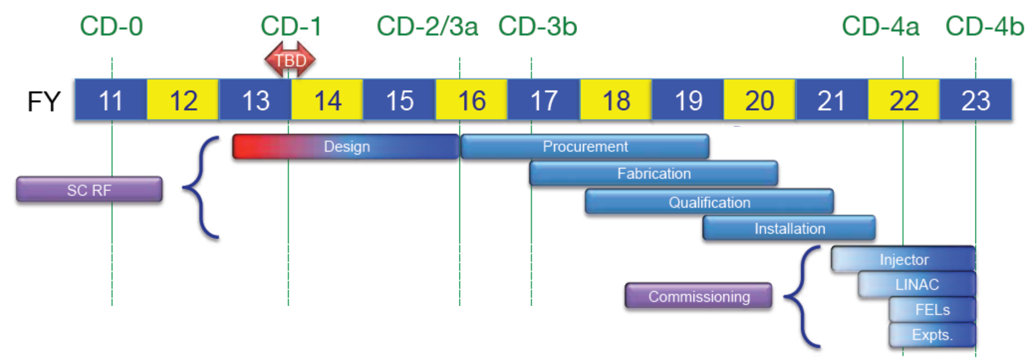
CW Soft X-Ray FEL Facility

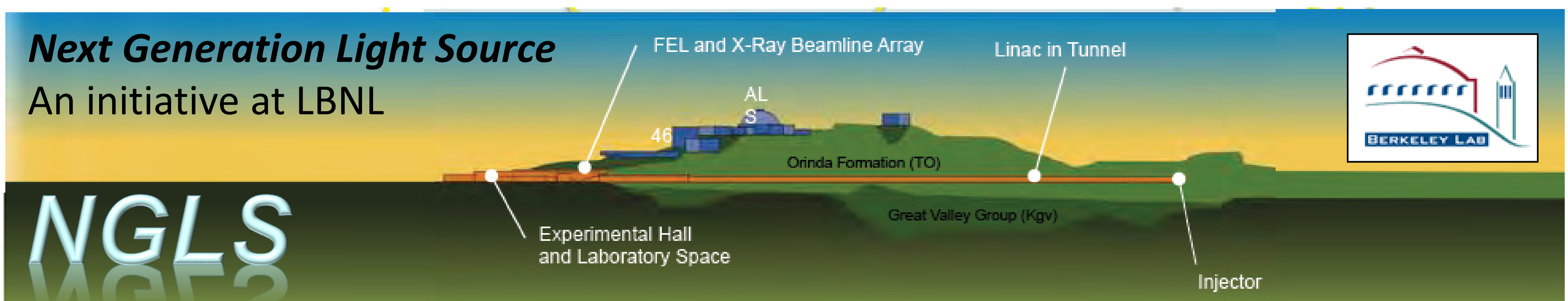
NGLS next generation light source | BERKELEY LAB | **LBNL**



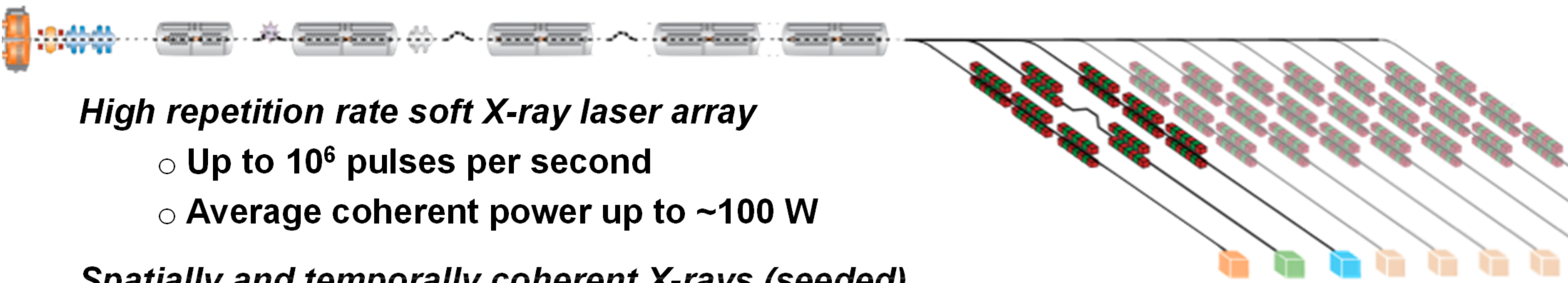
- Seeded FELs
- SC RF
- High rep-rate
- SC undulators
- 1-MW beam power
- Fast switching

Electron Beam Energy	2.4	GeV
FEL Wavelength Range	1 - 4.6	nm
Linac Beam Rate (CW)	1	MHz
Avg. Linac Current	0.3	mA
First Operation	2023	-





What is the NGLS?
Capabilities



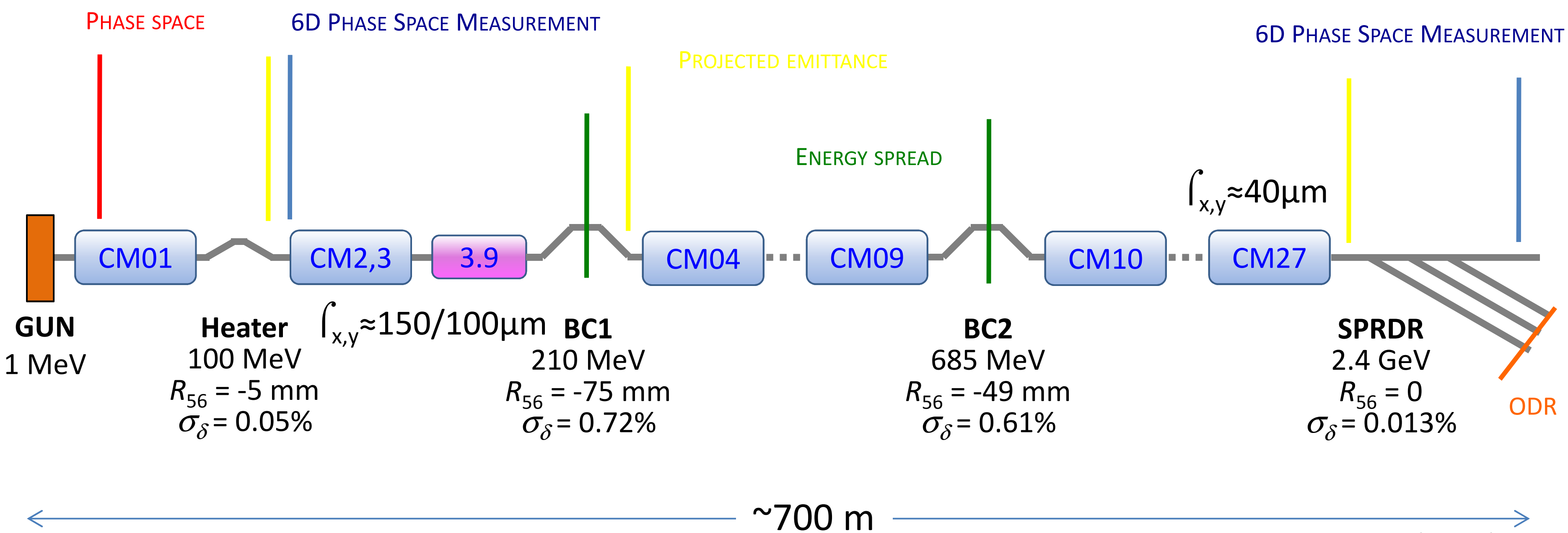
High repetition rate soft X-ray laser array
- Up to 10^6 pulses per second
- Average coherent power up to ~100 W

Spatially and temporally coherent X-rays (seeded)
- Ultrashort pulses from ≤1 fs to ~100 fs
- Narrow energy bandwidth to 50 meV

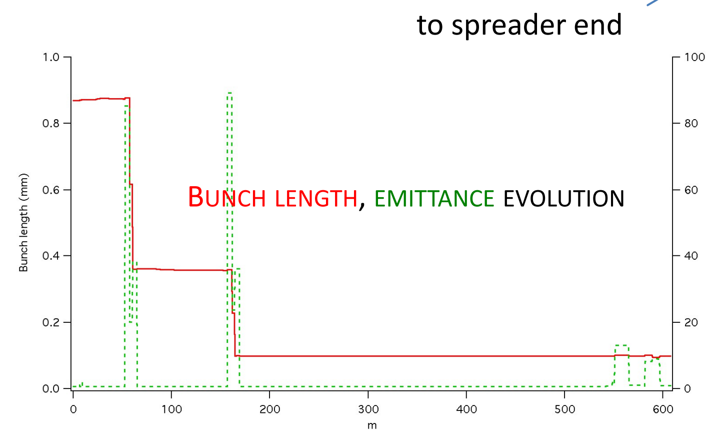
Tunable X-rays
- Adjustable photon energy from 270 eV – 1.2 keV
  - higher energies in the 3rd and 5th harmonics
- Polarization control
- Moderate to high flux with 10^8 – 10^{12} photons/pulse

Expandable
- Capability
- Capacity

Planned Electron Beam Diagnostics



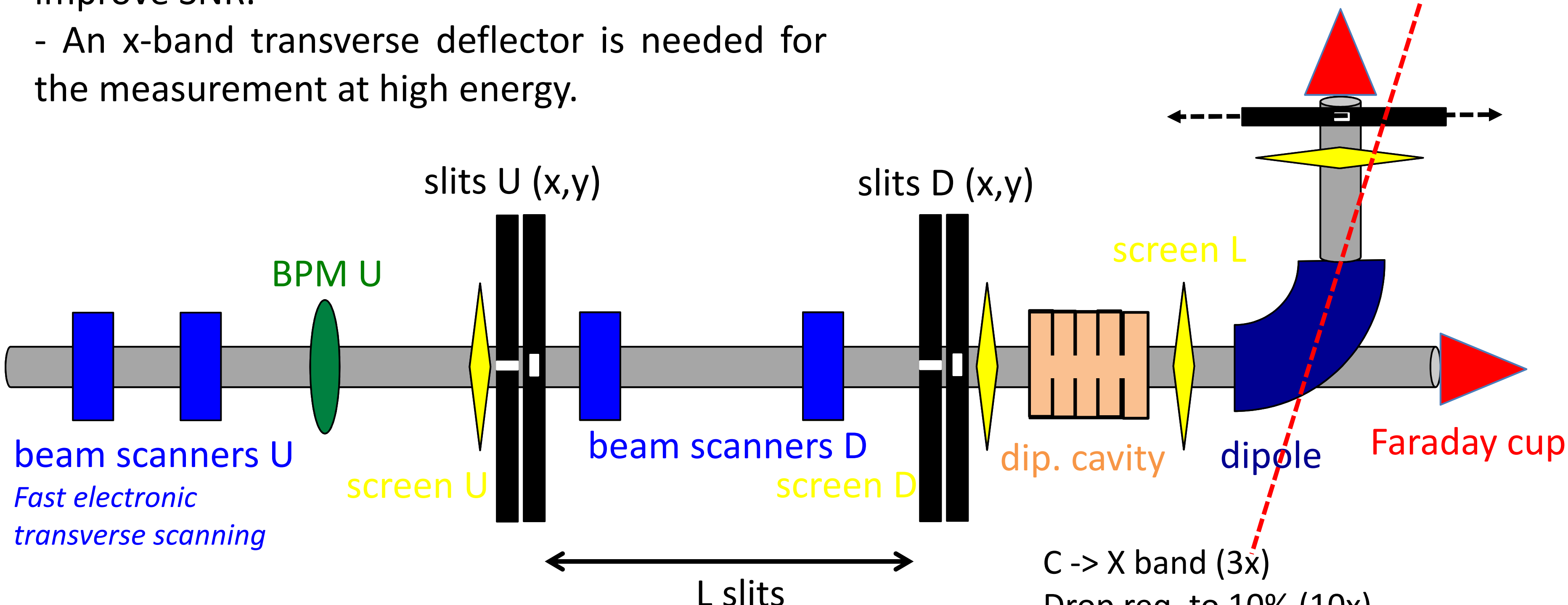
- ~16 MV/m gradient (CW)
- 27 ~12-m long cryo-modules
- 7 RF cavities per module?
- 2 bunch compressors
- 1 laser heater (damps µ-bunching instability)
- 3 spreader beamlines + straight-ahead dump



6D Phase-Space Measurement

- Sweeping the high rep. rate beam across the slits allows for a fast reconstruction of the longitudinal and transverse phase space.
- Slices with fewer particles can be integrated to improve SNR.
- An x-band transverse deflector is needed for the measurement at high energy.

Beam Energy (MeV)	σ_z (μm)	σ_x (μm)	Req. V_{RF} for $\sigma_z/100$ resolution (3.9 GHz)
85	870	150	1.8 MV
2400	100	40	120 MV

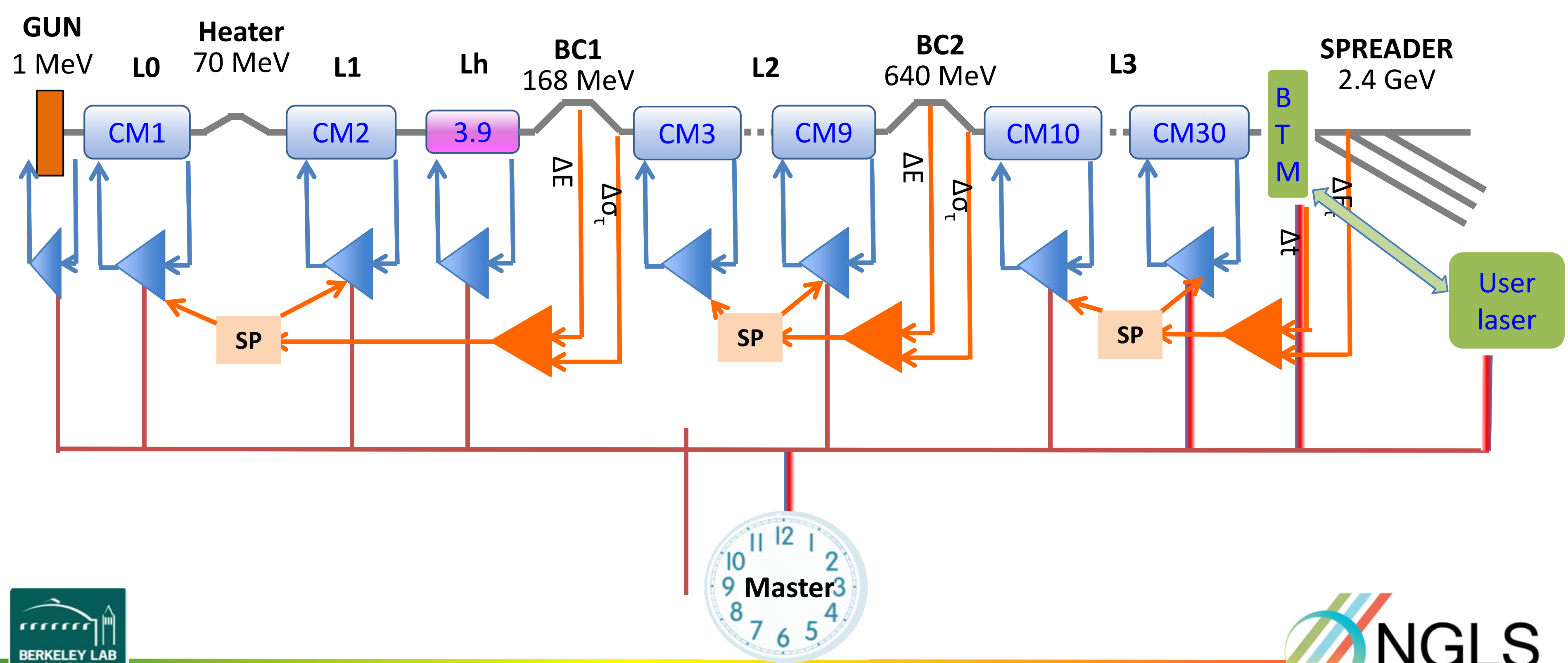


Fixed slits system (Cornell ERL)

C -> X band (3x)
Drop req. to 10% (10x)
more realistic 4 MV
Bunch rolloff: 0.7 THz!)

RF Feedback and Timing Distribution System

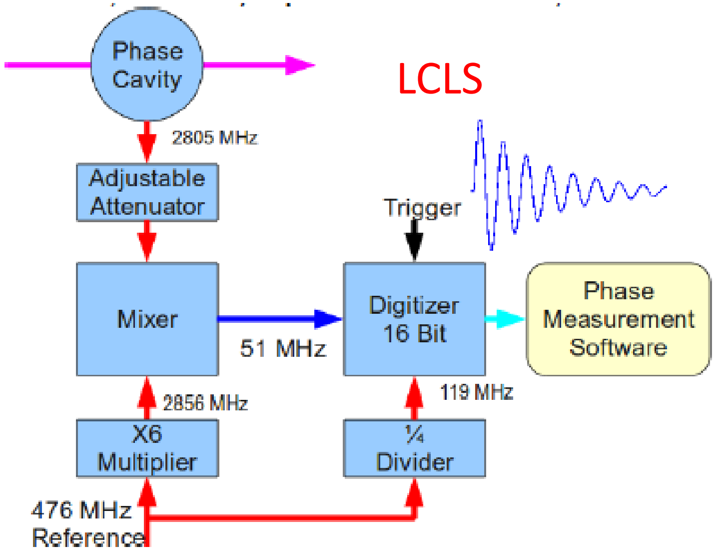
- RF Control – 0.01%,0.01 deg at 1.3 GHz
- Beam-based Feedback
- Optical synchronization between arrival time and user lasers- ~1 fsec
- Stabilized clock reference distribution - <10 fsec



BERKELEY LAB

NGLS next generation light source

Beam Timing Monitor

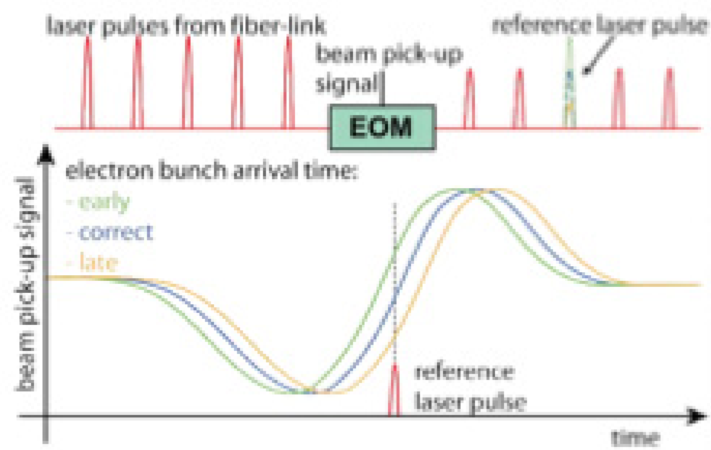


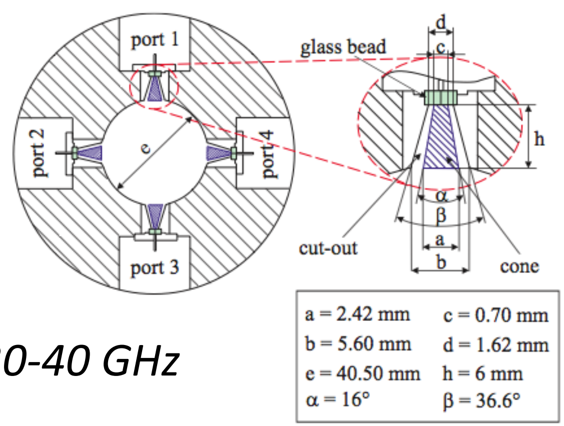
LCLS

- Resolutions of few 10's of femtosecond are achievable.
- For high rep. rate beams, ringing in RF based monitors can be an issue
- Electro-optic measurements make use of components developed for communication industry.

RF-based

Laser based





30-40 GHz

High bandwidth pickup (A. Angelosvski et al.)

F. Lohel - FLASH

High Beam Power Survival Guide

- Minimally Invasive Diagnostics
  - *Laser Wire, etc.*
    - Low signal levels are compensated by averaging at high repetition rate.
- Off-Axis Diagnostic
  - *Necessary for high beam impedance devices (higher frequency RF cavities) or delicate OTR screens.*
    - Bunch can be branched out entirely for destructive measurements, or induced transverse oscillations can be used to steer bunch across non-destructive device.
- Keep off the beam entirely
  - *Use bunch wake field, synchrotron radiation, ODR.*

Conclusions

- Measuring low-emittance, short bunches, at high repetition rate presents particular challenges and diagnostics need to be designed accordingly.
- When the beam has been made sufficently stable the high repetiotion rate turns into a substantial advantage and allows measurements which would not otherwise be possible.
- It seems absolutely worthwhile to pursue the construction of accelerators dedicated to this type of diagnostics.