Overview of Gun and Linac FEL Experimental Results

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Overview of Gun and Linac FEL Experimental Results

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Topics

- Motivation
- RF Gun and Linac Technologies
- SASE and RAFEL Experimental Results

Historical Background

1984 SASE Theory (Bonifacio et al.)

1985 1D Solution (Wang & Yu)

1985 First SASE Experiment (LLNL)

1986 3D Theory (Kim)

1987 Photoinjector (Sheffield et al.)

1989 Second SASE Experiment (MIT)

1996 SASE at 20-40 μm (Okuda et al.)

1997 SASE at 5-10 μm (Prazeres et al.)

1997 SASE at 0.5-1 (Babzien et al.)

1997 SASE Fluctuations (Hogan et al.)

1998 SASE Gain of 300 (Nguyen et al.)

1998 SASE Gain of 3×10^5 (Hogan et al.)

1998 Microbunching (Tremaine et al.)

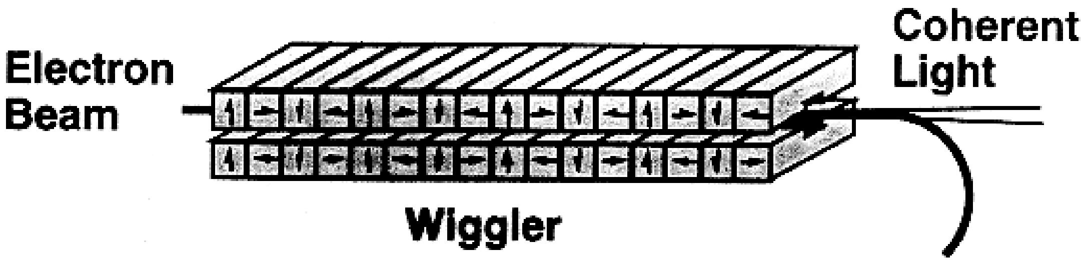
Projected performance

- Wavelength 1.5 Å (range 1.5-15 Å)
- Electron energy 14.35 GeV (range 14.35-4.54)
- Norm. emittance 1.5 π mm mrad (rms)
- Peak current 3,400 A
- Bunch length 230 fs
- FEL parameter, ρ 4.7 10^{-4}
- Gain length 11 m

- Undulator length 112 m
- Undulator gap 6 mm
- Undulator par., K 3.7

- Saturation peak power 9 GW
- Peak brightness 1.2 10^{33}
- Average brightness 4.2 10^{22}

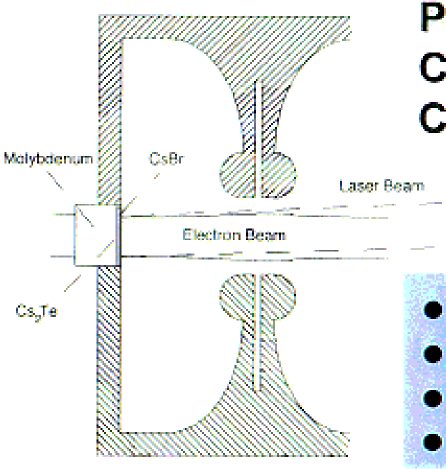
Requirements for SASE Experiments



- High current density
- Long wiggler with two-plane focusing
- Low emittance $\varepsilon \leq \frac{\lambda}{4\pi}$
- Small energy spread $\frac{\Delta\gamma}{\gamma} < \rho$
- Low diffraction $\frac{z_R}{L_G} > 1$
- Small slippage parameter $\frac{l_s}{c\tau} \ll 1$

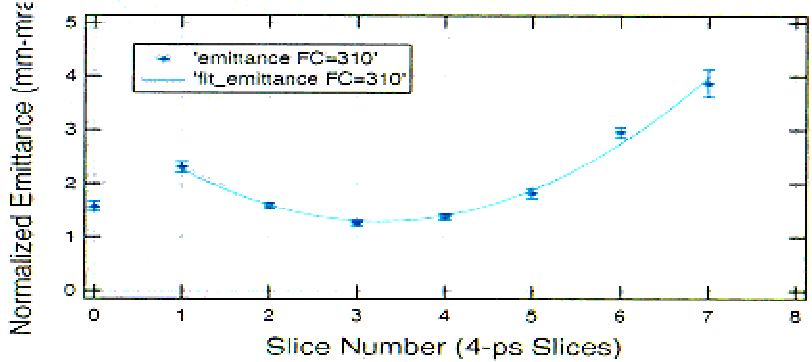
High-current Electron Beams needed for LCLS Are Being Developed at Los Alamos and SLAC

Photoinjector with CsBr-coated Cs_2Te Cathodes



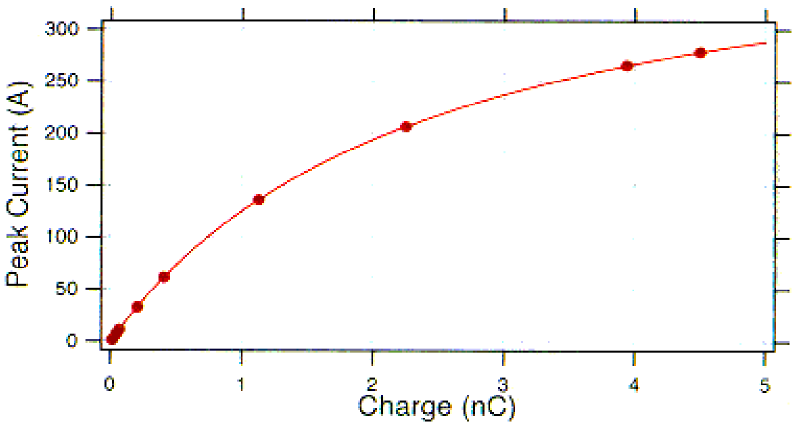
- High Q.E.
- Rugged
- Long lifetime
- Low dark current

Measurement of Slice Emittance



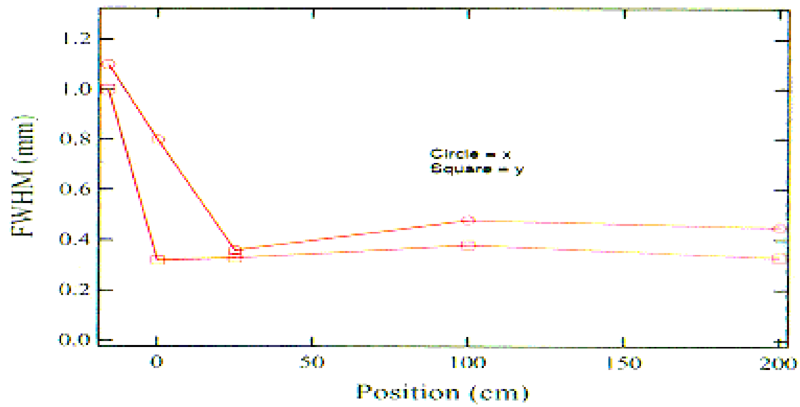
- Average Emittance = 2 mm-mrad @ 1 nC

Direct Production of High-current Beams



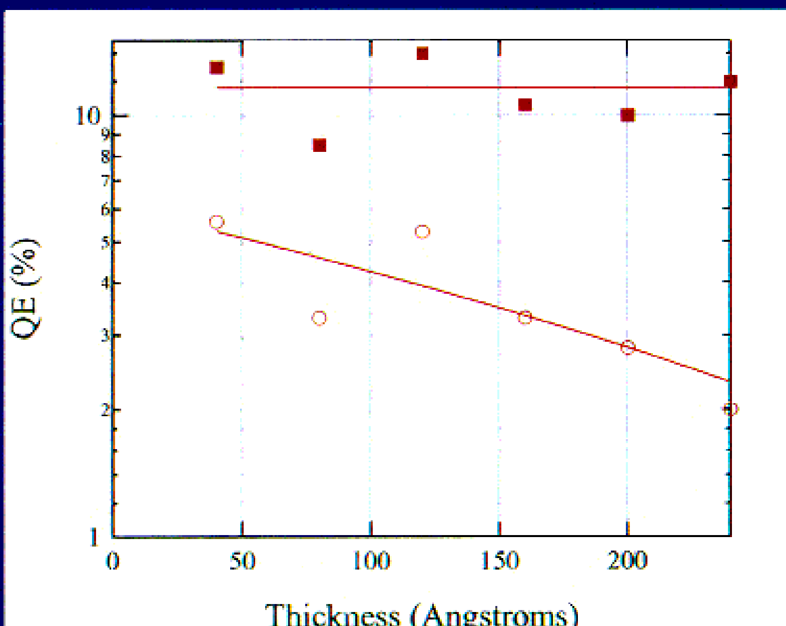
- Current < 300 A can be generated directly

Focusing High-Current Electron Beams

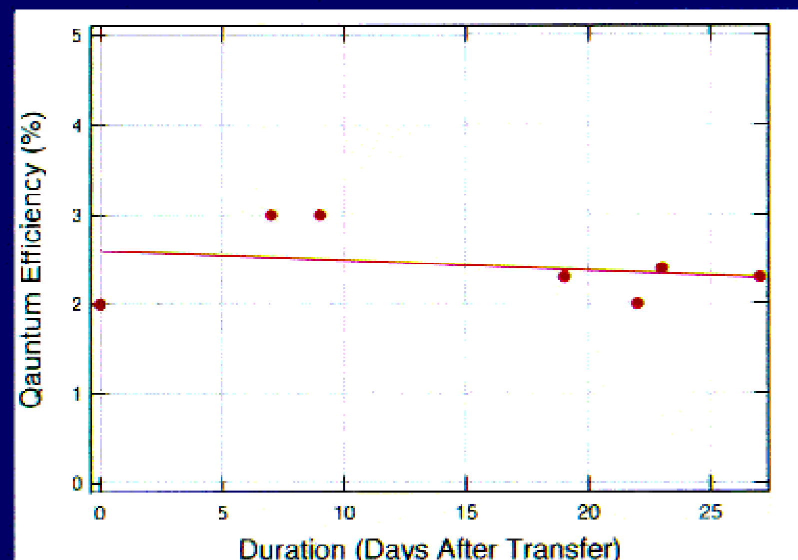


- Current density > 10^5 A/cm^2 was measured

CsBr-coated Cs_2Te Cathodes Have Lower QE and Longer Life

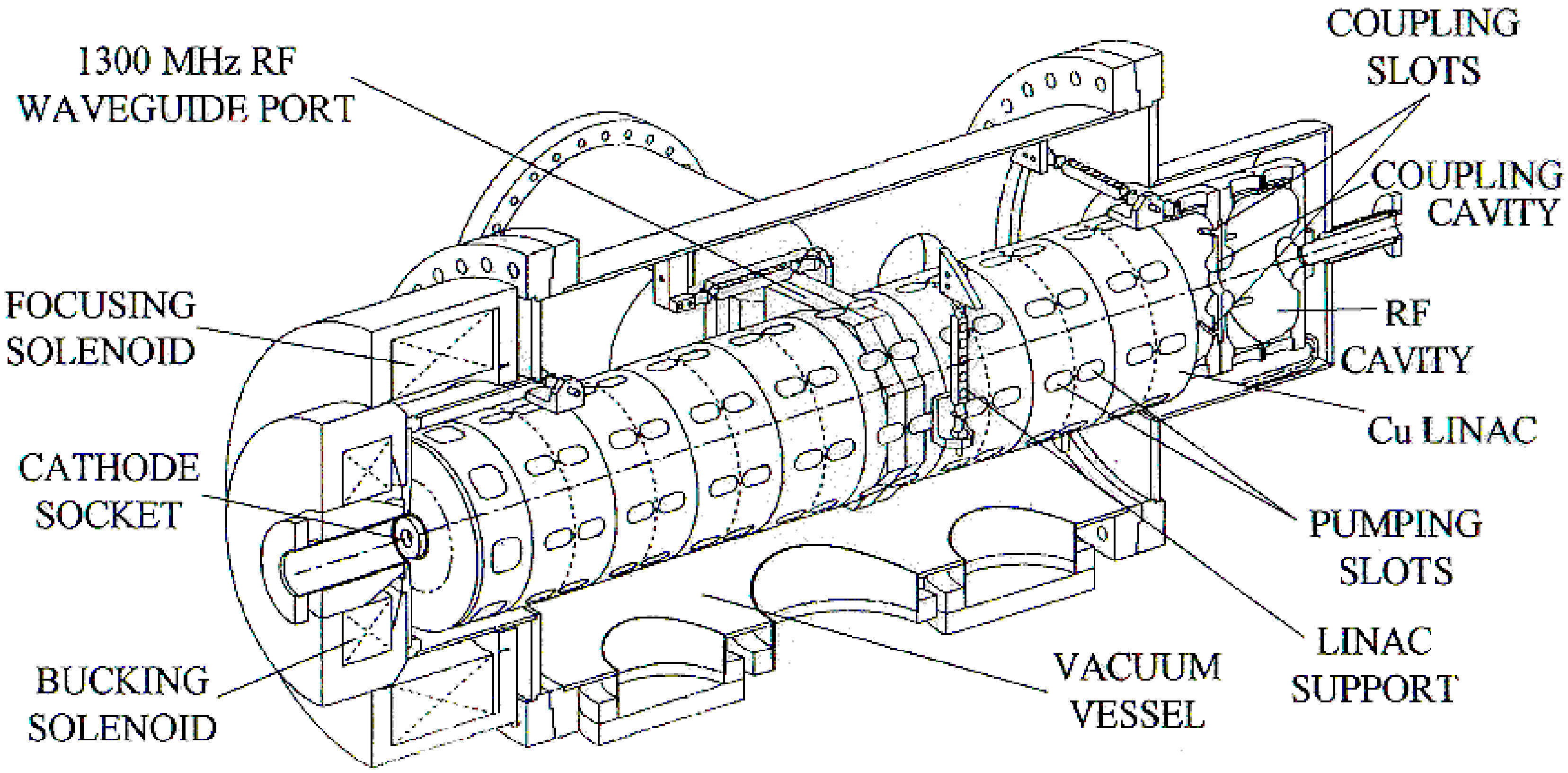


Semi-log plot of QE of uncoated (top) and coated (bottom) cathodes versus CsBr thickness.

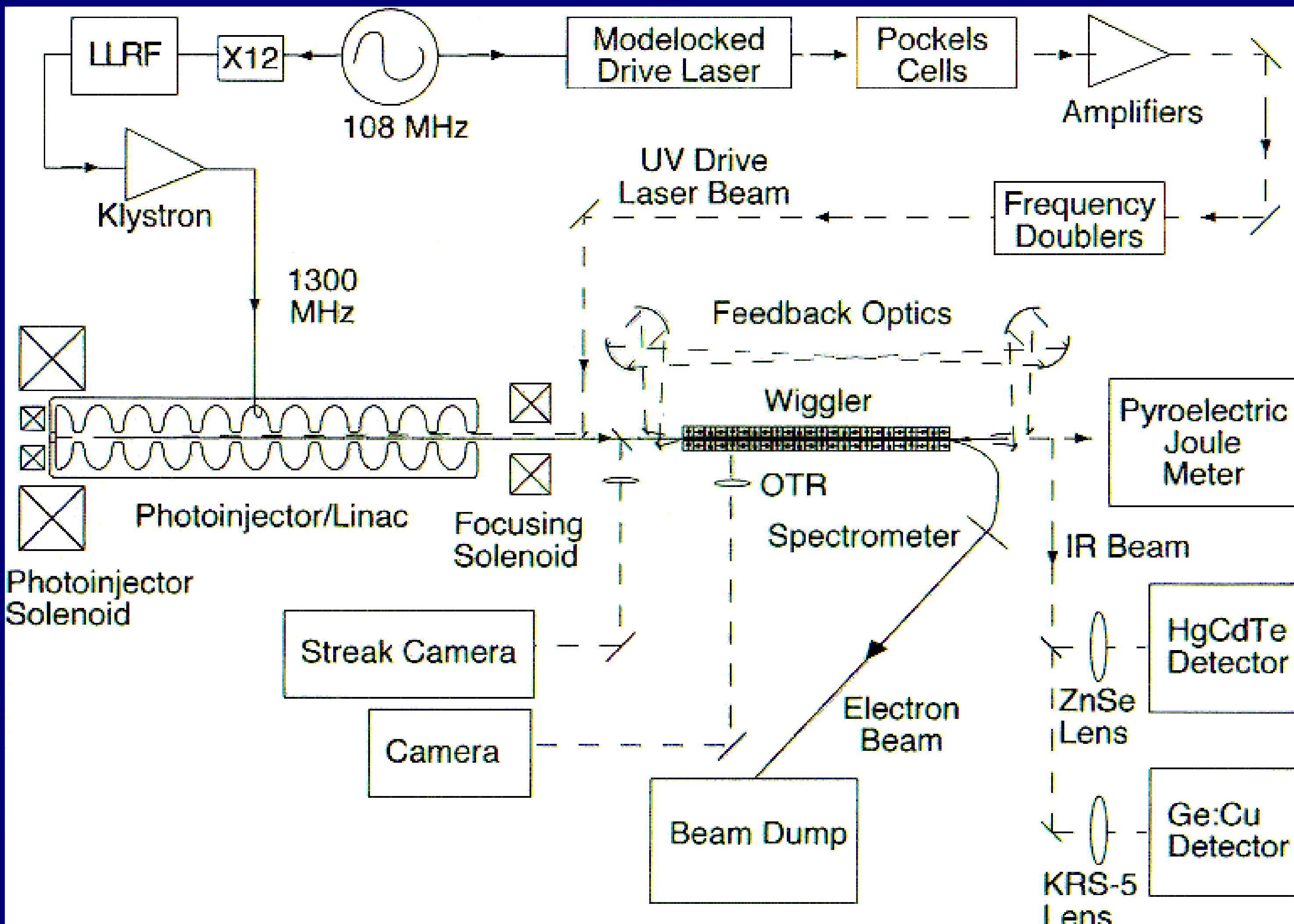


Plot of QE vs duration in days. Within experimental errors, coated cathode QE remains unchanged for several days.

AFEL LINAC


1300 MHz RF
WAVEGUIDE PORT
COUPLING
SLOTS
COUPLING
CAVITY
FOCUSING
SOLENOID
RF
CAVITY
Cu LINAC
CATHODE
SOCKET
PUMPING
SLOTS
LINAC
SUPPORT
BUCKING
SOLENOID
VACUUM
VESSEL

RAFEL Experimental Setup



Metal Photocathodes

Pros

- Robust
- Able to Operate in High Fields

Con

- Low QE

Semiconductor Cathodes

Pros

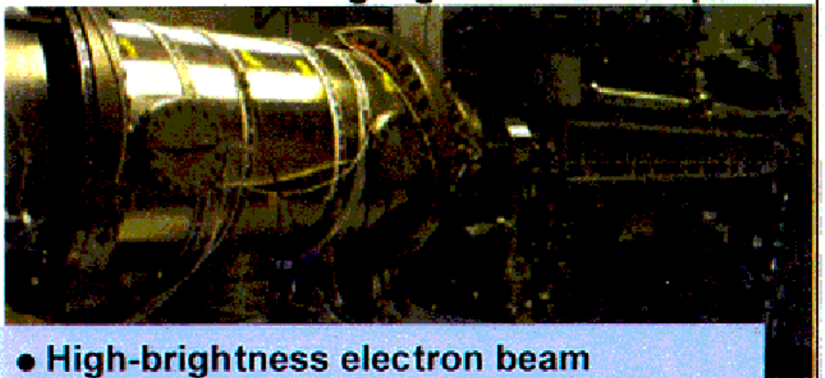
- High QE
- Can Produce Multiple Pulses

Con

- Untested High-Field Operation

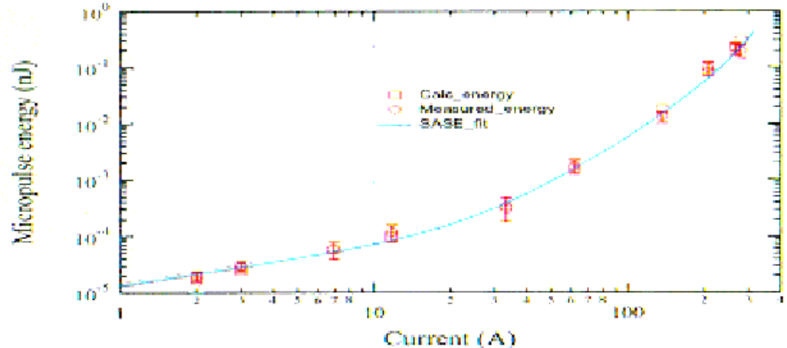
The LCLS Collaboration Measured Large SASE Gains on the Advanced FEL at Los Alamos

Test-stand for High-gain SASE Expts.



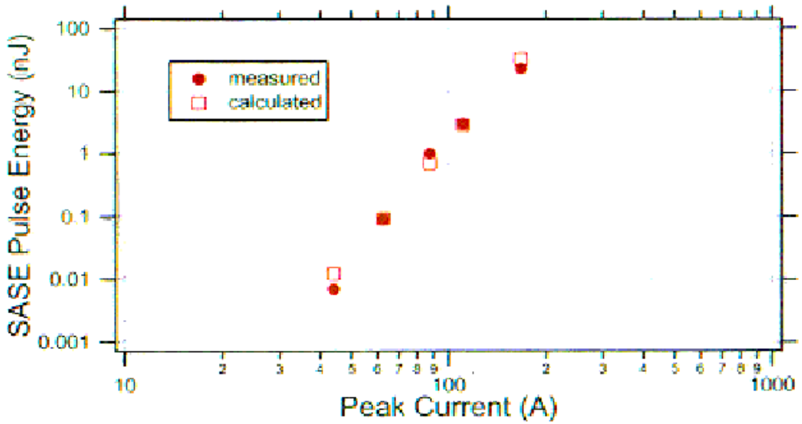
- High-brightness electron beam
- Diagnostics for electrons and photons

First Measurement of Large SASE Gain



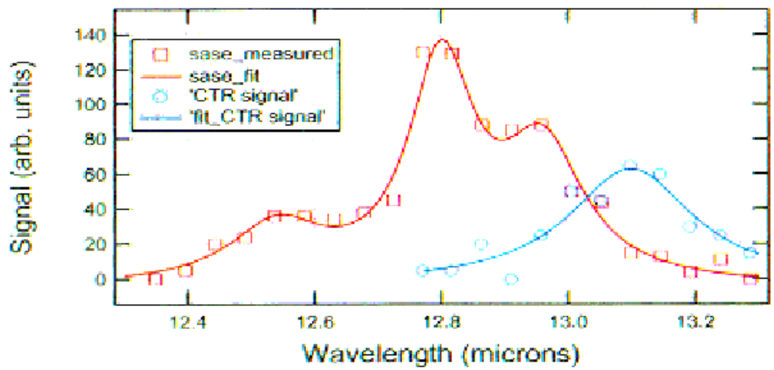
- Gain = 300 for the one-meter undulator

Measurement of Largest SASE Gain



- Gain = 10^5 for the two-meter undulator

Observation of SASE-induced bunching



- Observation of coherent transition radiation
- Results corroborate SASE measurements

SASE MODEL

POWER SPECTRUM

$$\left.\frac{dP}{d\omega}\right|_z = \frac{9}{32} \cdot \frac{eI}{c\epsilon_0} \cdot \frac{a_w^2 L_g [J_0(\xi) - J_1(\xi)]^2}{\lambda_w (1 + a_w^2)} \cdot e^{z/L_g}$$

$$L_g = \frac{\lambda_w}{2\pi\sqrt{3}\rho}$$ FIELD GAIN LENGTH

$$\rho = \frac{1}{\gamma}\left[\frac{a_w \lambda_w JJ}{4\sqrt{2}\pi\sigma}\right]^{\frac{2}{3}} \left[\frac{I}{I_A}\right]^{\frac{1}{3}}$$ PIERCE PARAMETER

$$\frac{\Delta\omega}{\omega} = \sqrt{\frac{\rho}{N_w}}$$ RELATIVE BANDWIDTH

Analytic Model for Calculating SASE Power vs. Wiggler Length

$$P_{SASE} = \frac{1}{9}\frac{P_{startup}e^{z/L_G}}{1+\frac{P_{startup}}{9P_{sat}}\left(e^{z/L_G}-1\right)}$$

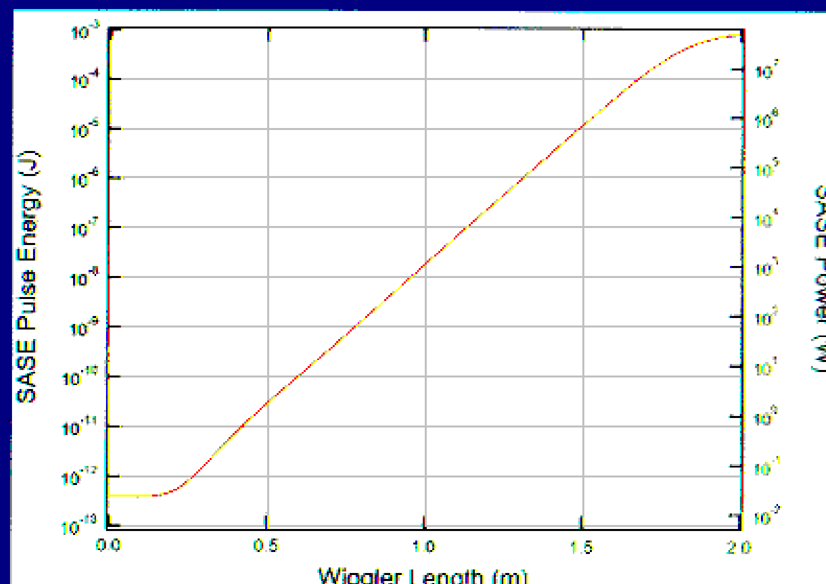
$$P_{startup} = \frac{9}{32}\frac{eI}{c\varepsilon_0}\frac{a_w^2 JJ^2}{1+a_w^2}\frac{L_G}{\lambda_w}\omega\sqrt{\frac{\rho}{N_w}}$$

$$P_{sat} = \rho P_{beam}$$

Dattoli Model for Saturation

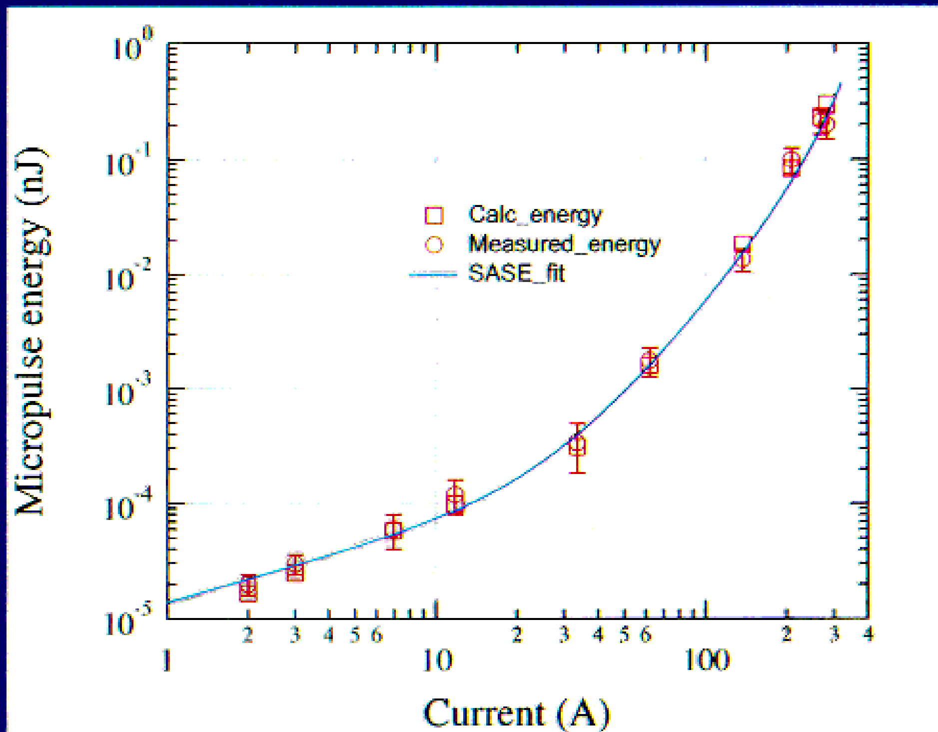
Yu Model for Startup

Calculations agree with Measurements



First SASE Experiment at LANL Achieves 300X Single-Pass Gain

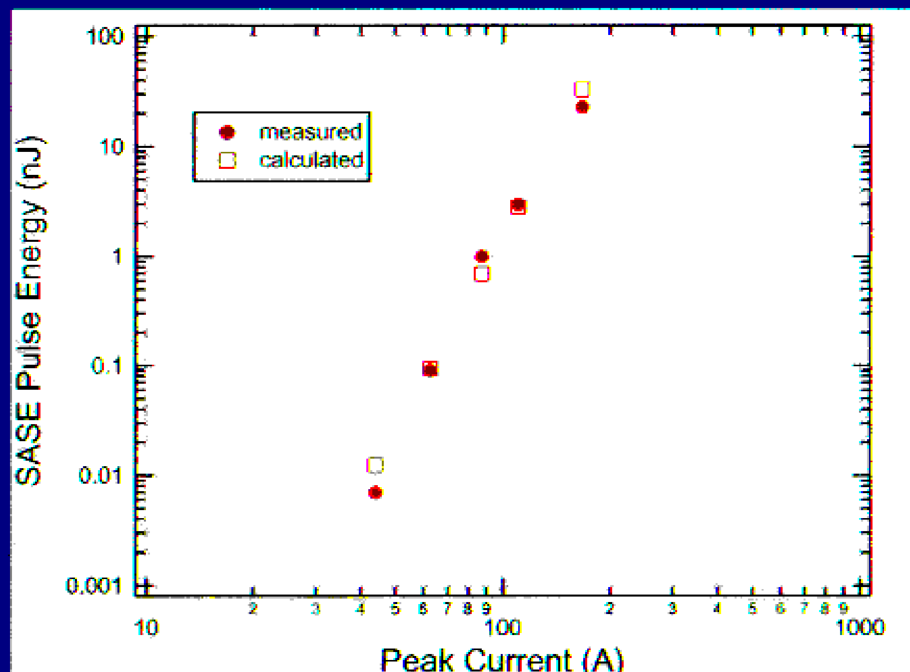
- 1-m Uniform wiggler, rms $a_w = 0.92$
- SASE pulse energy was measured as a function of charge.
- From current dependence on Q, plot SASE pulse energy versus I.
- Fit measurements to predicted dependence and obtain SASE gain versus I.
- Analytical calculations agree with measurements.



Log-log plot of measured and predicted SASE pulse energy versus current

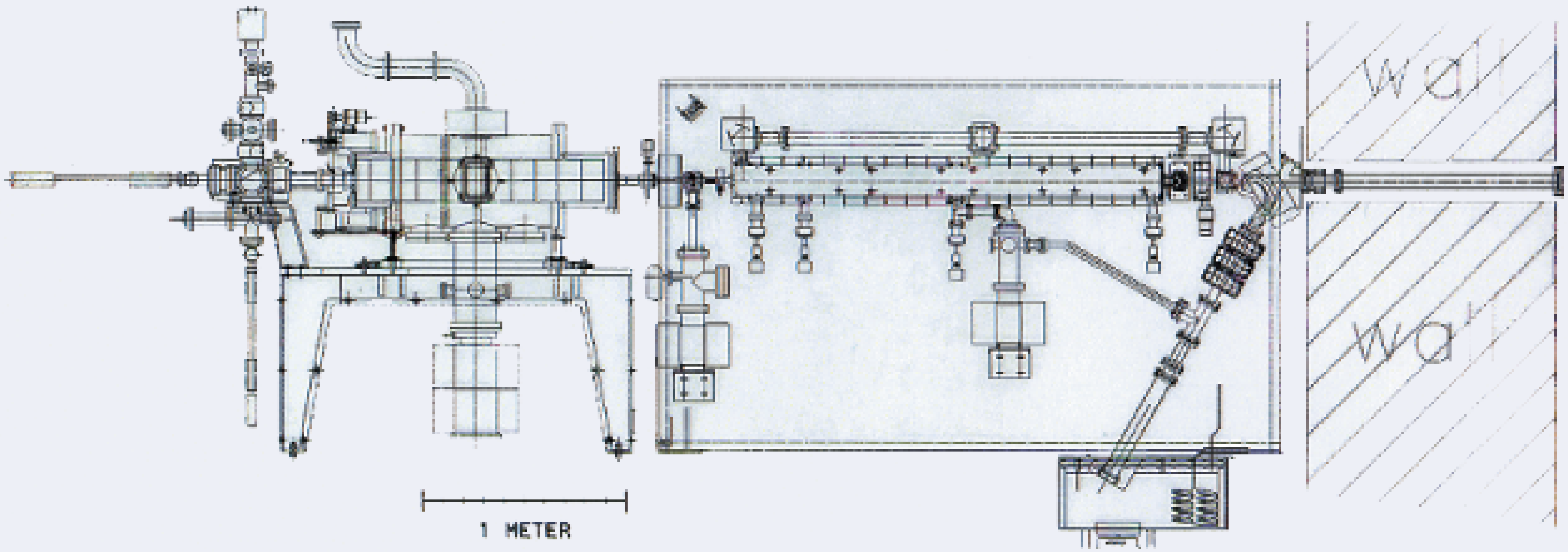
UCLA-LANL-RRC-SLAC Joint SASE Achieves $3x10^5$ Gain

- 2-m Uniform wiggler rms $a_w = 0.7$
- Calculated saturation length = 2.9 meters
- Highest SASE gain in the infrared to date
- Fluctuations agree with prediction of 8.8 cooperation lengths
- Measured pulse energy agrees with predictions.



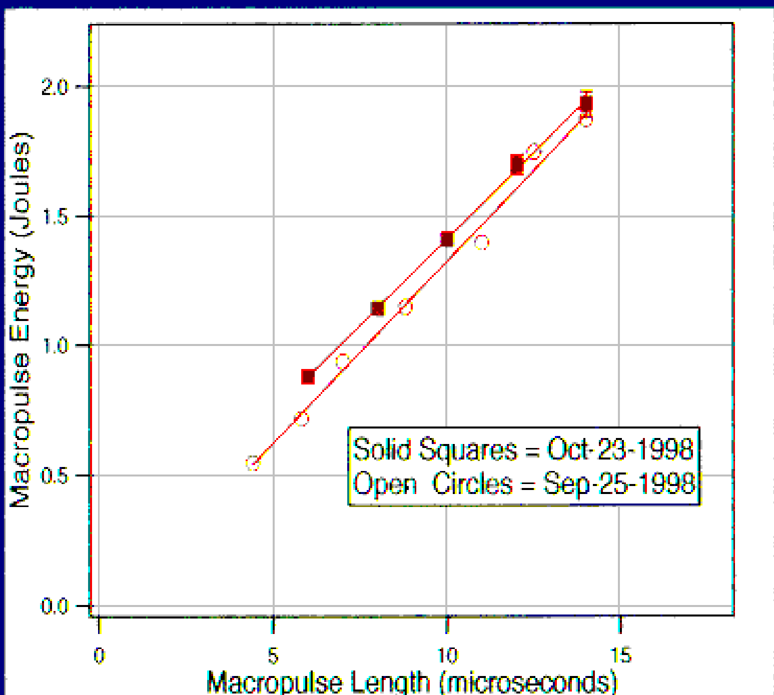
Log-log plot of measured and predicted pulse energy vs current

SCHEMATIC OF THE ADVANCED FEL MODIFIED FOR THE RAFEL DEMONSTRATION

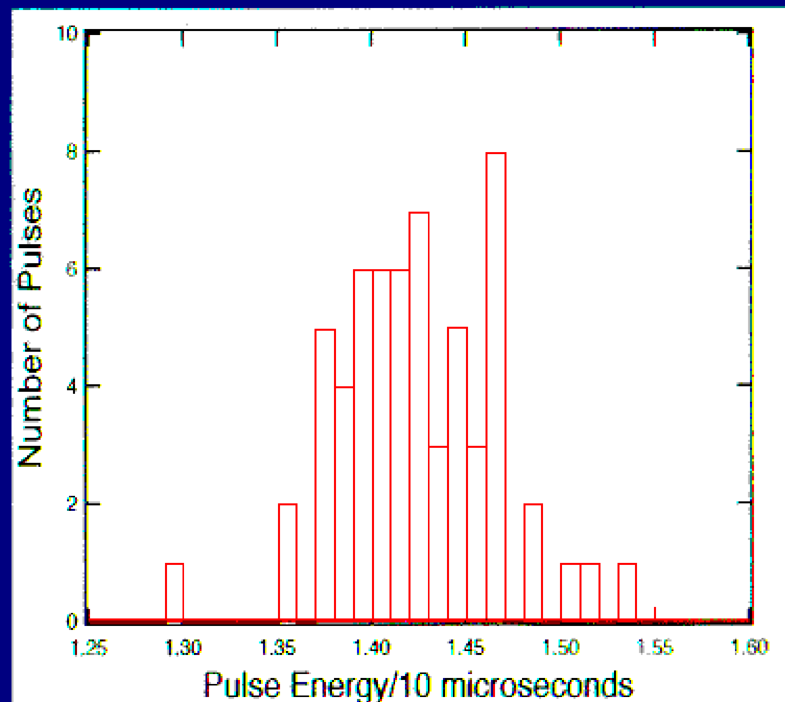


The linac is on the left. The beamline consists of a straight section to accomodate a 2 m long wiggler, shown here on a 4 ft x 10 ft vertical optical table. The electron beam is focused at the wiggler entrance by a single solenoid. The electron beamexiting the wiggler follows a 120 degree bend and terminates in the beam dump. The high-power FEL optical beam is directed forward and exits the radiation vault through a hole in the wall.

RAFEL Macropulse Energy Is Reproducibly 1.44 J in 10 μs



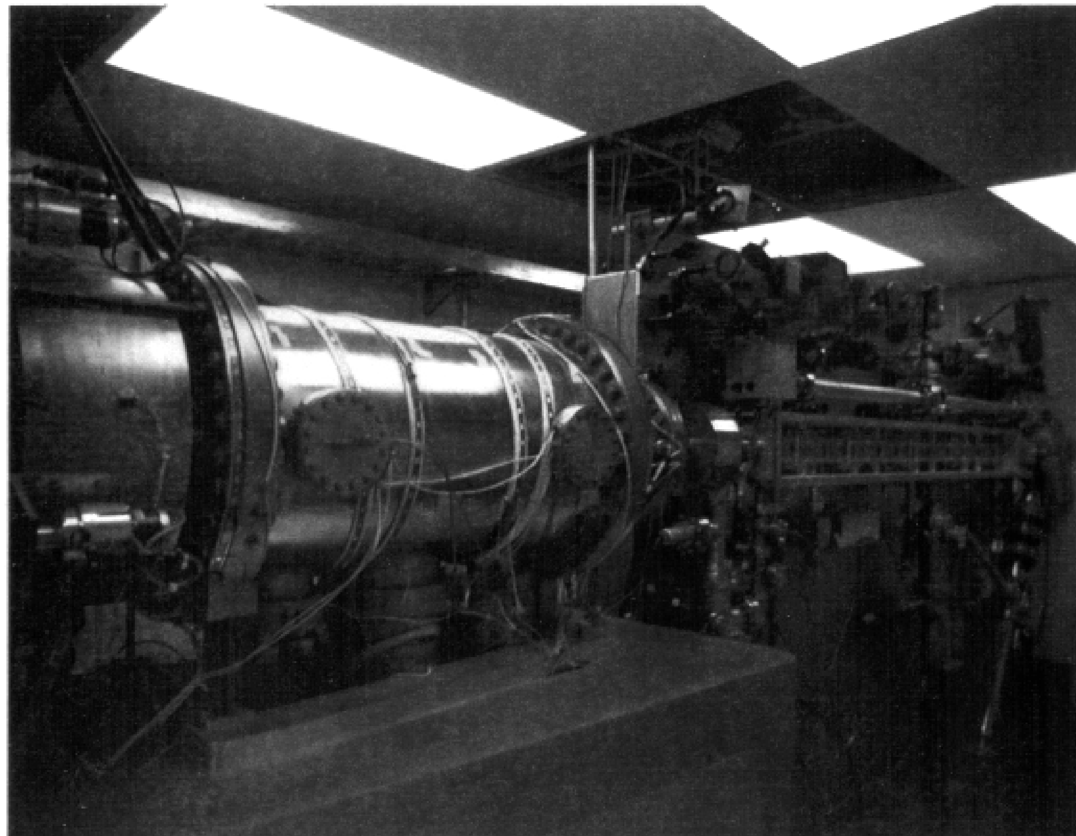
Plot of measured macropulse energy versus length for two different runs



Histogram of macropulse energy

High-Power RAFEL Achieves 2.1 J per 14-μs pulse (150 kW)

- $E_b = 16.7$ MeV
- $I_{peak} = 265$ A
- $I_{macropulse} = 0.5$ A
- $E_b = 8.4$ MW
- IR pulse = 14 μs
- $\lambda = 16.3$ μm
- $W_{IR} = 2.1$ joules
- $P_{IR} = 150$ kW
- $P_{ave} = 13.7$ W



Conclusions

- **Existing Gun Technologies Can Support LCLS Design**
- **Experimental Results Up to Now Agree with SASE Theory**
- **Relevant Experiments Are Underway to Test SASE Predictions**