High Stability Electron Beam Regeneration by Longitudinal Feedback using HGHG output

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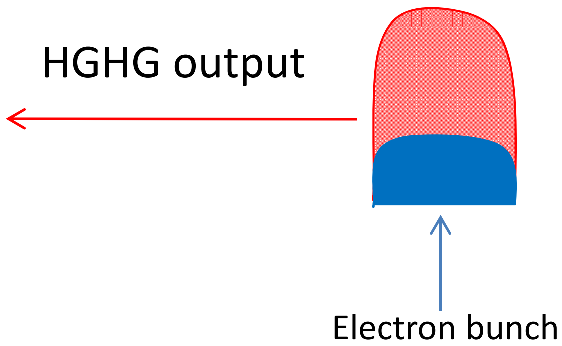
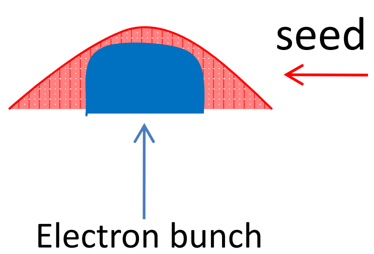
Basic idea

•When seed laser pulse is longer than the electron bunch, the HGHG output is perfectly synchronized with the electron bunch.
•When HGHG output is sent back to cathode it carries the information about the phase and timing of the electron bunch
•When the HGHG output striking the cathode generates a second electron bunch, it realizes a feedback mechanism---the second electron bunch has energy and timing more close to design value and fluctuate less.

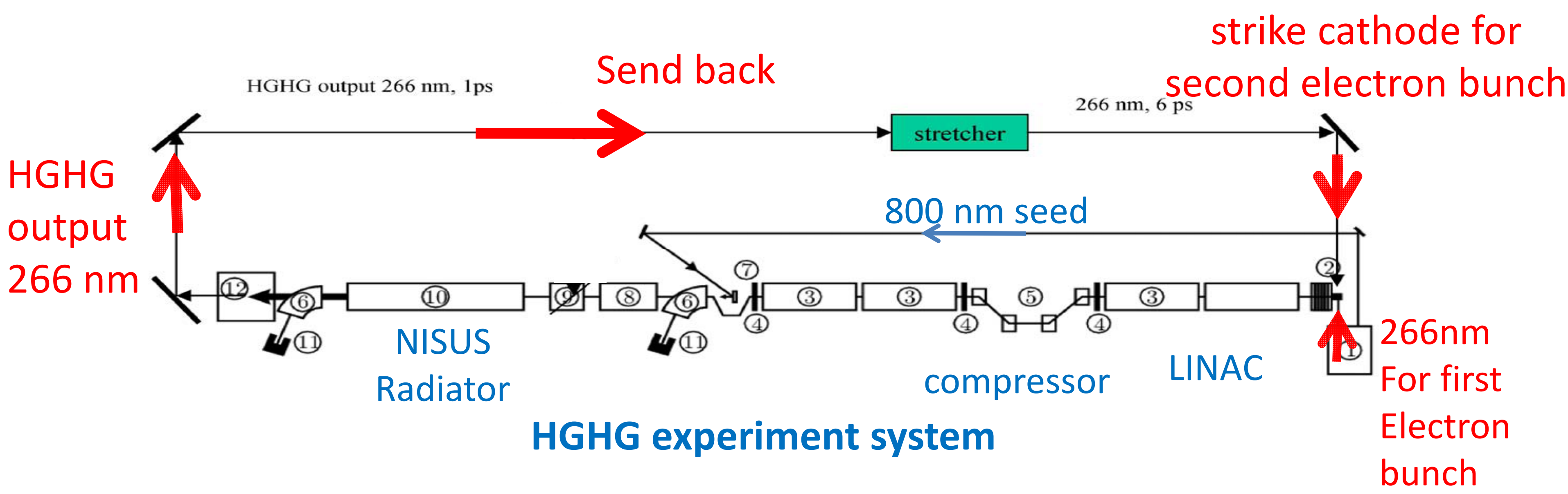




Basic principle

•First electron bunch interacts with seed to generate HGHG radiation
•Output of HGHG is sent back to cathode to generate second electron bunch
•If first electron bunch energy is higher than design value, its path length in compressor is shorter
•Output HGHG pulse strikes cathode earlier
•Because second electron bunch is earlier, its energy is lower than first → energy stabilized
•Energy jitter is reduced by compression ratio (for SDL, it is a factor 6-10)
•Similarly analysis is valid for arrival time → both energy and phase are stabilized

Illustration of Basic Principle



Extend to multi-bunches

- If output is split to seed second bunch, third electron bunch is more stable→ feedback
- For CW operation, stability will be determined by other noise sources such as mirror vibration (0.2μm).
- Charge and laser intensity feedback is can be achieved →need test from experiment

Split HGHG output to seed second bunch for multi pulses operation

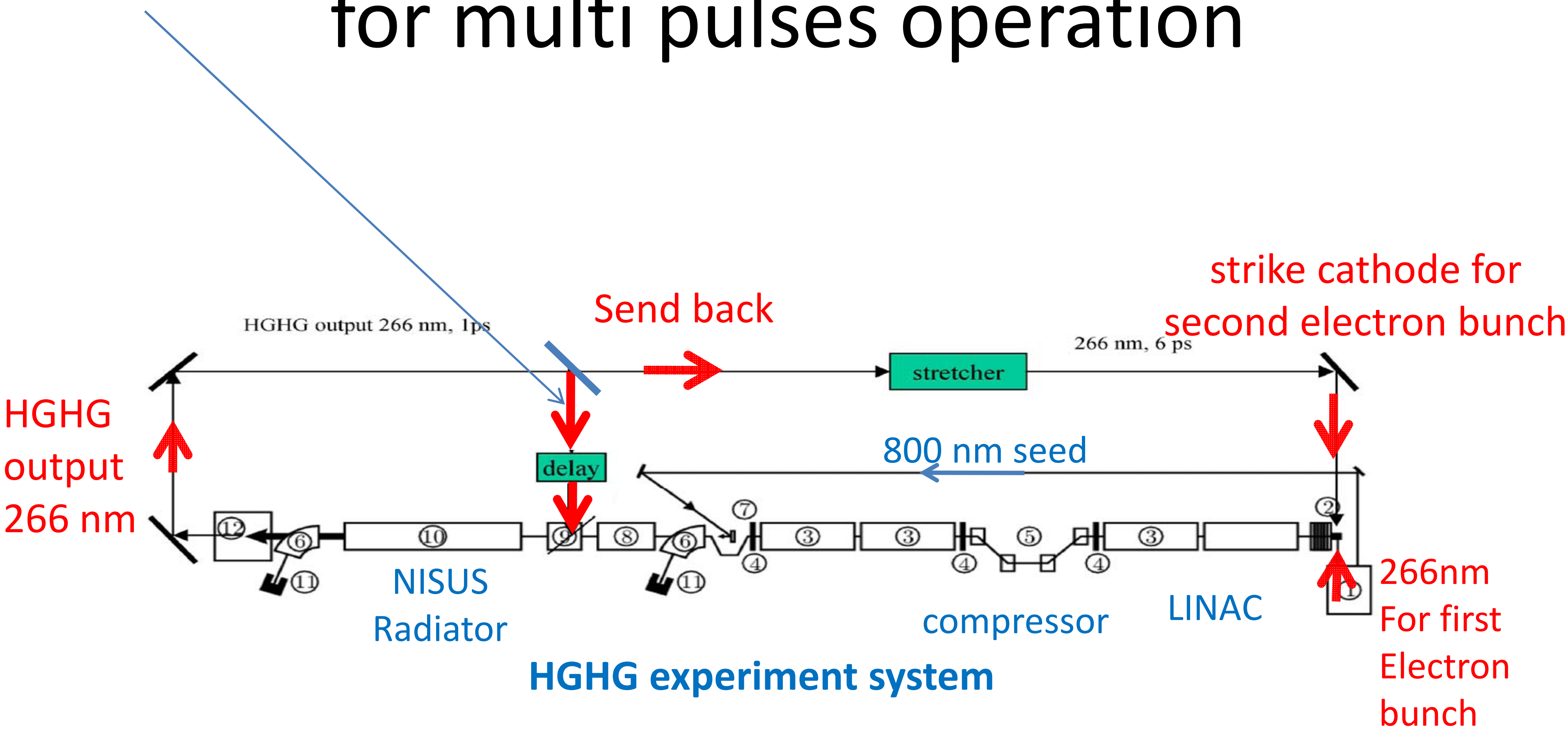
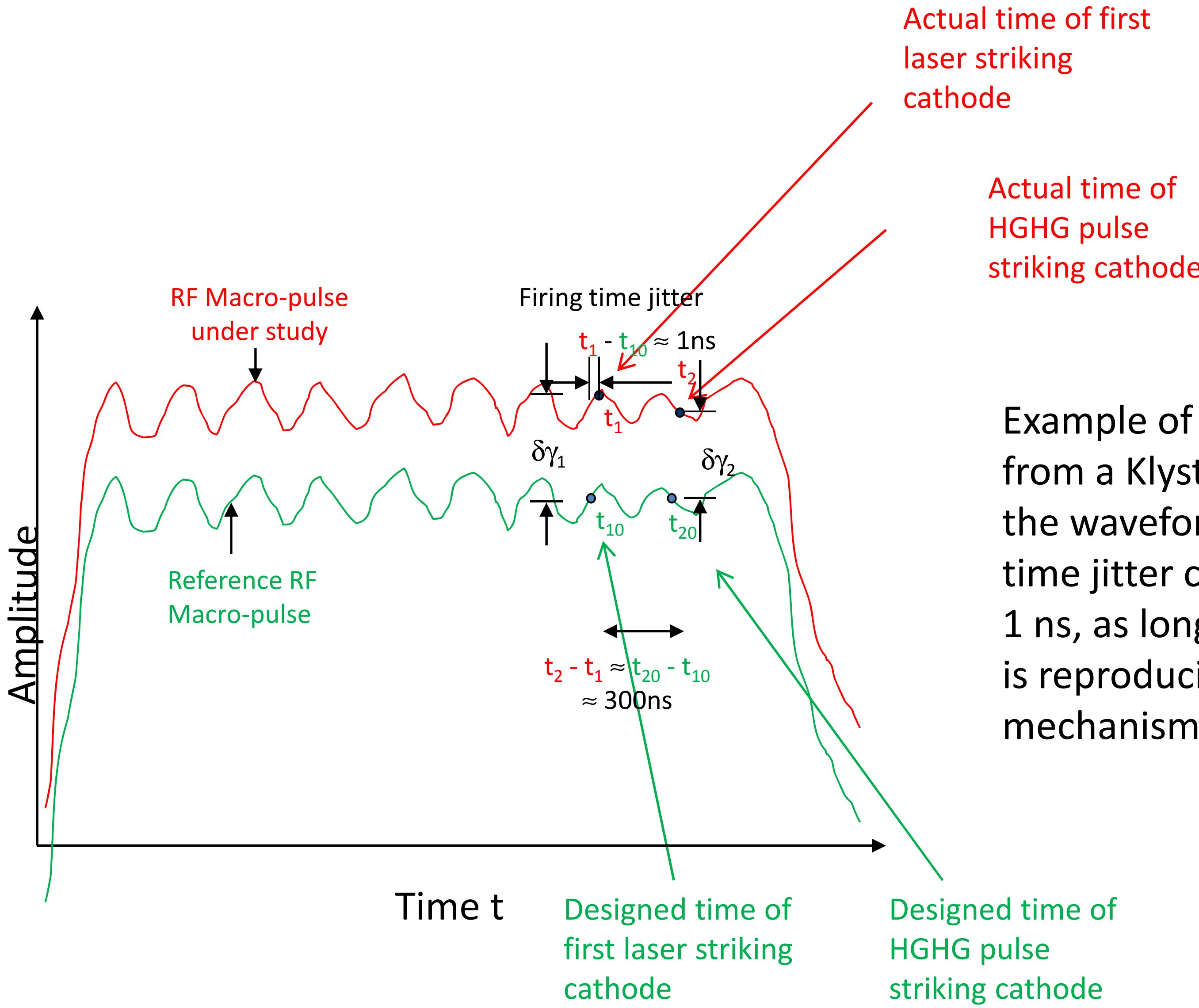


Illustration of feedback mechanism



Example of RF power derived from a Klystron: even though the waveform is irregular, and time jitter can be as much as 1 ns, as long as the waveform is reproducible, the feedback mechanism works

Effect of the laser pulse firing time jitter relative to the klystron firing time (t=0).

Energy fluctuation is reduced by compression ratio

The acceleration is on a slope $h \equiv \frac{d}{d\tau}\frac{\gamma}{\gamma_0}$

$$\frac{\Delta\gamma_1}{\gamma_0} = h\tau_1 + \frac{\delta\gamma_1}{\gamma_0}$$

τ_1 is time jitter of first laser pulse

$\delta\gamma_1$ is energy change due RF amplitude fluctuation

$\Delta\gamma_1$ is energy fluctuation of first electron bunch

$$\tau_2 = -R_{56}\frac{\Delta\gamma_1}{\gamma_0} + \tau_1$$

$$= -R_{56}\left(h\tau_1 + \frac{\delta\gamma_1}{\gamma_0}\right) + \tau_1 = (1 - R_{56}h)\tau_1 - R_{56}\frac{\delta\gamma_1}{\gamma_0}$$

τ_2 is time jitter of HGHG pulse

$$\frac{\Delta\gamma_2}{\gamma_0} = h\tau_2 + \frac{\delta\gamma_2}{\gamma_0} = h(1 - R_{56}h)\tau_1 - hR_{56}\frac{\delta\gamma_1}{\gamma_0} + \frac{\delta\gamma_2}{\gamma_0}$$

$$= (1 - R_{56}h)\left(h\tau_1 + \frac{\delta\gamma_1}{\gamma_0}\right) + \frac{\delta\gamma_2 - \delta\gamma_1}{\gamma_0} = (1 - R_{56}h)\frac{\Delta\gamma_1}{\gamma_0} + \frac{\delta\gamma_2 - \delta\gamma_1}{\gamma_0}$$

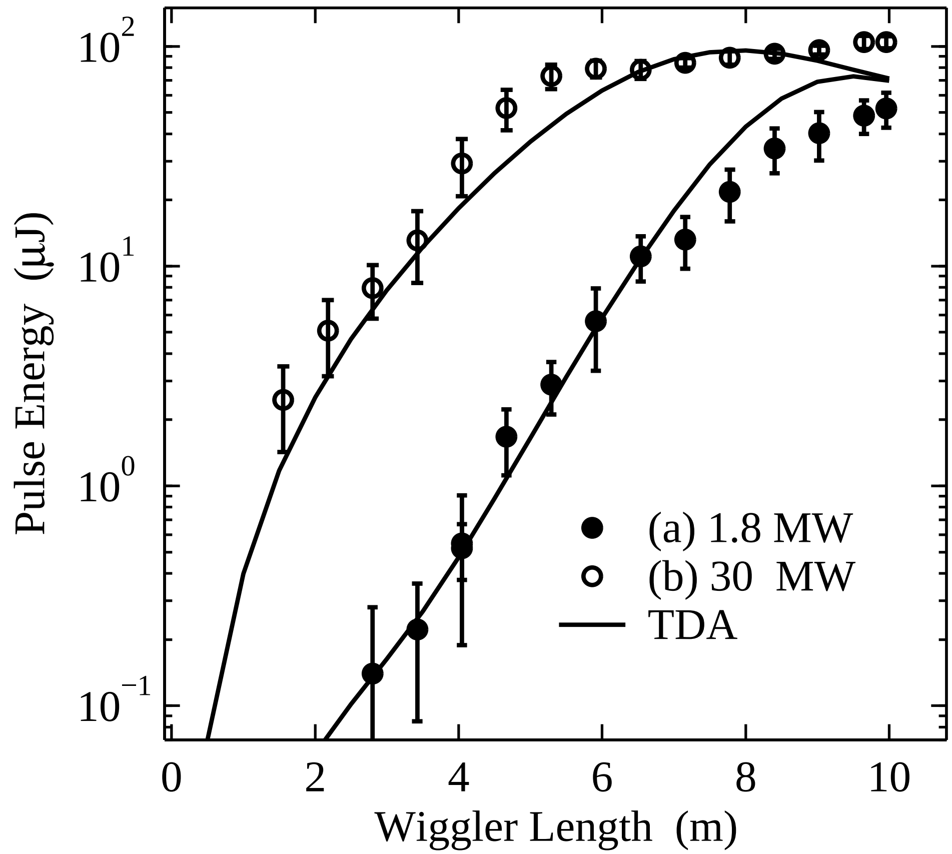
$\delta\gamma_2$ is energy change due RF amplitude fluctuation at the time of secon pulse

$\Delta\gamma_2$ is energy fluctuation of second electron bunch

Energy fluctuation is reduced by compression ratio $(1 - R_{56}h)$

$(\delta\gamma_2 - \delta\gamma_1)/\gamma_0$ is determined by waveform and is nearly a constant, so it does not contribute to fluctuation

Experiment at SDL shows that HGHG output is saturated in short distance and can provide stable pulse energy more than enough for cathode when seed power is set to appropriate value

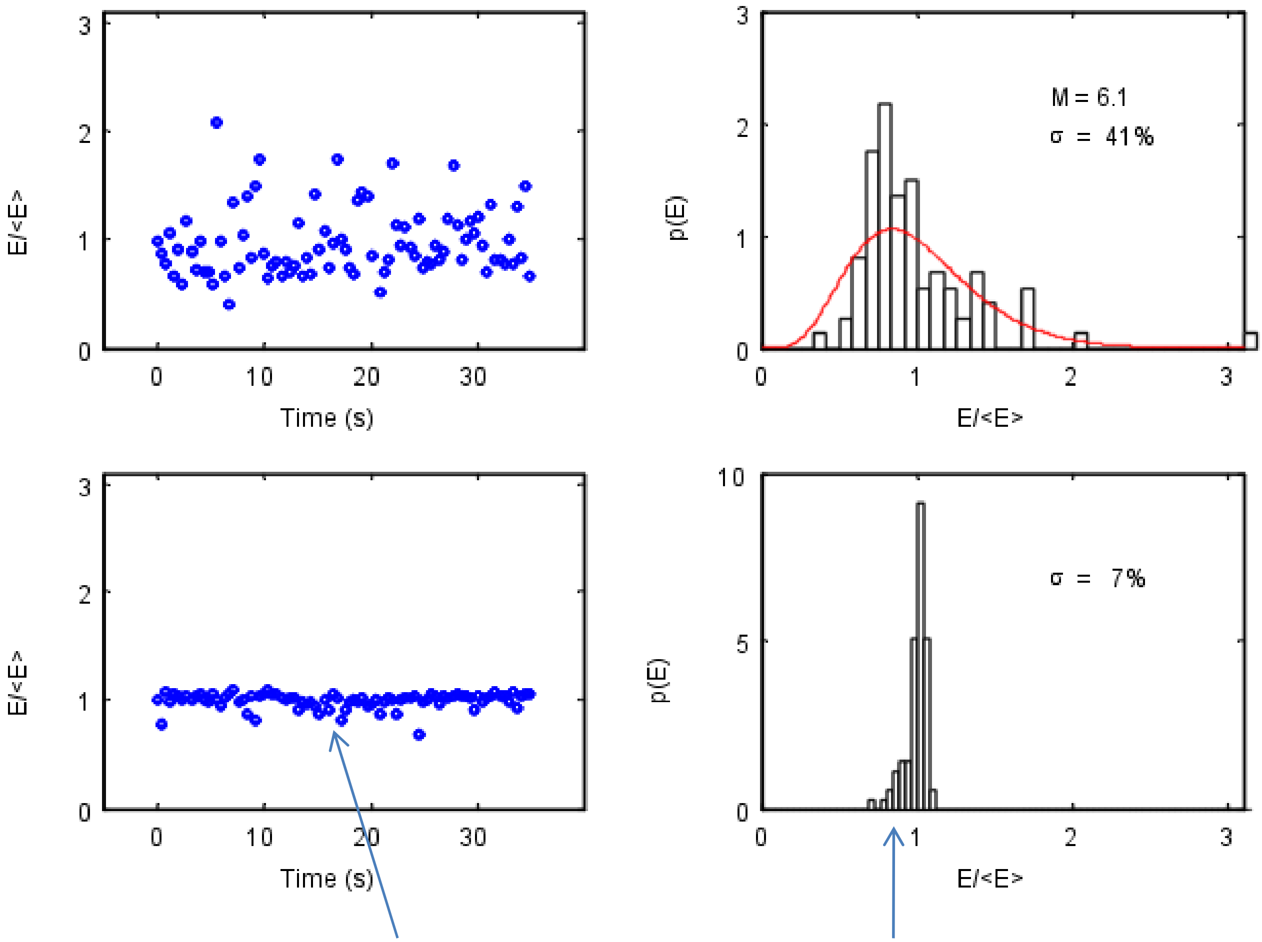


The HGHG experiment has generated more than 100 μJ stable operation while the cathode only need 60 μJ for 400 pC electron bunch. The example here electron beam energy is 178 MeV. High energy machine, need only very short wiggler and hence only small cost increase, and the output will be more than 1 mJ.

Shot to shot intensity fluctuation Shows high stability of HGHG output even for a linac without feedback

SASE

HGHG



The intensity variation here is due to RF phase drift and jitter, there is no feedback on RF phase

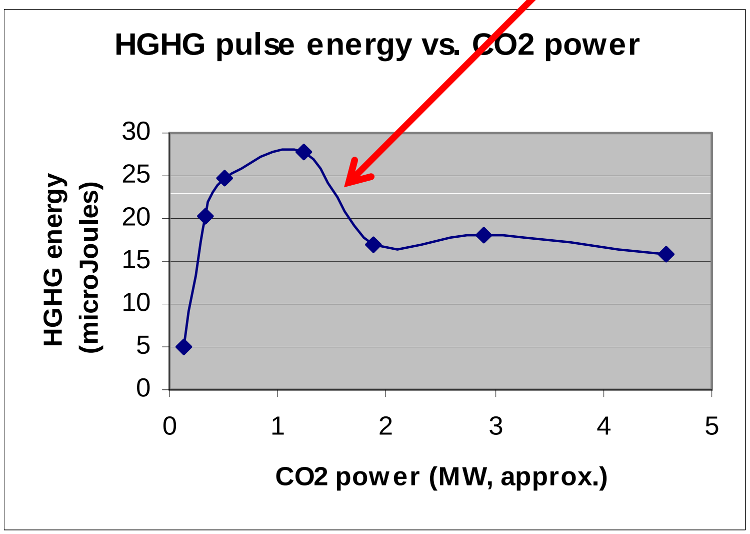
In addition to feedback on energy and phase stability, feedback on other properties can also be designed and tested

HGHG output vs. seed power is a curve determined by Bessel function. Seed power can be chosen to be on the falling slope of the Bessel curve

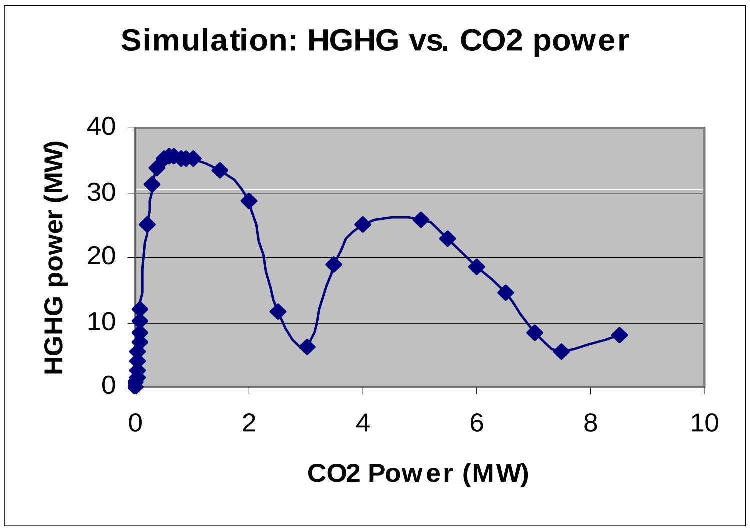
increased HGHG output→ increased seed → decreased HGHG output
→ stabilized HGHG →stabilized charge

Choose operating point

Experiment



Simulation



P_{out} (MW)

P_{in} (MW)

P_{in} (MW)

Pointing stability of laser pulse at cathode can also be similarly achieved by feedback

Future development and Applications

- Future X-ray FELs and possibly other next generation linac-based machines require unprecedented timing and energy stability --- Stability in existing x-ray FEL is a crucial issue.
- In a CW system, with new feedback mechanism implemented, a single laser pulse can trigger start the whole linac system operation—an ideal system for ERL.
- In system requiring very high average power laser as photo-cathode driver, the new method will provide a high stability laser source.
- Recent development of IR laser driver for RF gun photo-cathode will make it possible for a high average power IR source with a conventional single shot trigger laser. For current high average power cavity oscillator FEL system ,high power on mirror is a limitation. single pass FEL will solve the problem, hence possibility for higher average power----Possible industrial application, for example, for isotope separation