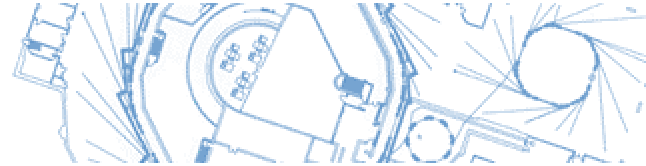
NSLS
NATIONAL SYNCHROTRON LIGHT SOURCE



Timing Jitter Requirements for the Linac System Based on a Photocathode RF gun

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Upton, NY 11973, USA

Presented at the FEL'03
September 9, 2003

Acknowledgement

This talk benefited greatly from discussion with following colleagues:

BNL: M. Babzien, A. Doyuran, H. Loss, J. Murphy, J. Rose, B. Sheehy, Z. Wu and L.H. Yu

ANL: W. Gai

SLAC: P. Emma and P. Krejcik

SHI and FESTA: A. Endo, K. Kobayashi, F. Sakai

And Many others. Thank you!

Outline

- Introduction
- What are the timing jitter requirements, what are effects.
- What can we do to reduce the timing jitter – Environments, laser oscillators, laser amplifier, klystron modulator?
- Timing jitter measurement techniques.
- Summary – 100 fs Ok, 50 fs maybe, 10 fs challenging

They all driven by a photocathode RF Gun Based Linac

RESEARCH ARTICLES

Exponential Gain and Saturation of a Self-Amplified Spontaneous Emission Free-Electron Laser

S. V. Milton,[1*] E. Gluskin,[1] N. D. Arnold,[1] C. Benson,[1] W. Berg,[1] S. G. Biedron,[1,2] M. Borland,[1] Y.-C. Chae,[1] R. J. Dejus,[1] P. K. Den Hartog,[1] B. Deriy,[1] M. Erdmann,[1] Y. I. Eidelman,[1] M. W. Hahne,[1] Z. Huang,[1] K.-J. Kim,[1] J. W. Lewellen,[1] Y. Li,[1] A. H. Lumpkin,[1] O. Makarov,[1] E. R. Moog,[1] A. Nassiri,[1] V. Sajaev,[1] R. Soliday,[1] B. J. Tieman,[1] E. M. Trakhtenberg,[1] G. Travish,[1] I. B. Vasserman,[1] N. A. Vinokurov,[3] X. J. Wang, G. Wiemerslage,[1] B. X. Yang[1]

VOLUME 88, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 2002

Generation of GW Radiation Pulses from a VUV Free-Electron Laser Operating in the Femtosecond Regime

V. Ayvazyan,[4] N. Baboi,[7,16] I. Bohnet,[5] R. Brinkmann,[4] M. Castellano,[8] P. Castro,[4] L. Catani,[10] S. Choroba,[4] A. Cianchi,[10] M. Dohlus,[4] H. T. Edwards,[6] B. Faatz,[4] A. A. Fateev,[13] J. Feldhaus,[4] K. Flöttmann,[4] A. Gamp,[4] T. Garvey,[14] H. Genz,[3] Ch. Gerth,[4] V. Gretchko,[11] B. Grigoryan,[19] U. Hahn,[4] C. Hessler,[3] K. Honkavaara,[4] M. Hüning,[17] R. Ischebeck,[17] M. Jablonka,[1] T. Kamps,[5] M. Körfer,[4] M. Krassilnikov,[2] J. Krzywinski,[12] M. Liepe,[7] A. Liero,[17] T. Limberg,[4] H. Loos,[3] M. Luong,[1] C. Magne,[1] J. Menzel,[17] P. Michelato,[9] M. Minty,[4] U.-C. Müller,[4] D. Nölle,[4] A. Novokhatski,[2] C. Pagani,[9] F. Peters,[4] J. Pflüger,[4] P. Piot,[4] L. Plucinski,[7] K. Rehlich,[4] I. Reyzl,[4] A. Richter,[3] J. Rossbach,[4] E. L. Saldin,[4] W. Sandner,[15] H. Schlarb,[7] G. Schmidt,[4] P. Schmüser,[7] J. R. Schneider,[4] E. A. Schneidmiller,[4] H.-J. Schreiber,[5] S. Schreiber,[4] D. Sertore,[9] S. Setzer,[2] S. Simrock,[4] R. Sobierajski,[4,18] B. Sonntag,[7] B. Steeg,[4] F. Stephan,[5] K. P. Sytchev,[13] K. Tiedtke,[4] M. Tonutti,[17] R. Treusch,[4] D. Trines,[4] D. Türke,[17] V. Verzilov,[8] R. Wanzenberg,[4] T. Weiland,[2] H. Weise,[4] M. Wendt,[4] I. Will,[15] S. Wolff,[4] K. Wittenburg,[4] M. V. Yurkov,[13,*] and K. Zapfe[4]

VOLUME 88, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 2002

Experimental Characterization of Nonlinear Harmonic Radiation from a Visible Self-Amplified Spontaneous Emission Free-Electron Laser at Saturation

A. Tremaine,[1] X. J. Wang,[2] M. Babzien,[2] I. Ben-Zvi,[2] M. Cornacchia,[3] H.-D. Nuhn,[3] R. Malone,[2] A. Murokh,[1] C. Pellegrini,[1] S. Reiche,[1] J. Rosenzweig,[1] and V. Yakimenko[2]
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(Received 20 September 2001; published 3 May 2002)

VOLUME 91, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2003

First Ultraviolet High-Gain Harmonic-Generation Free-Electron Laser

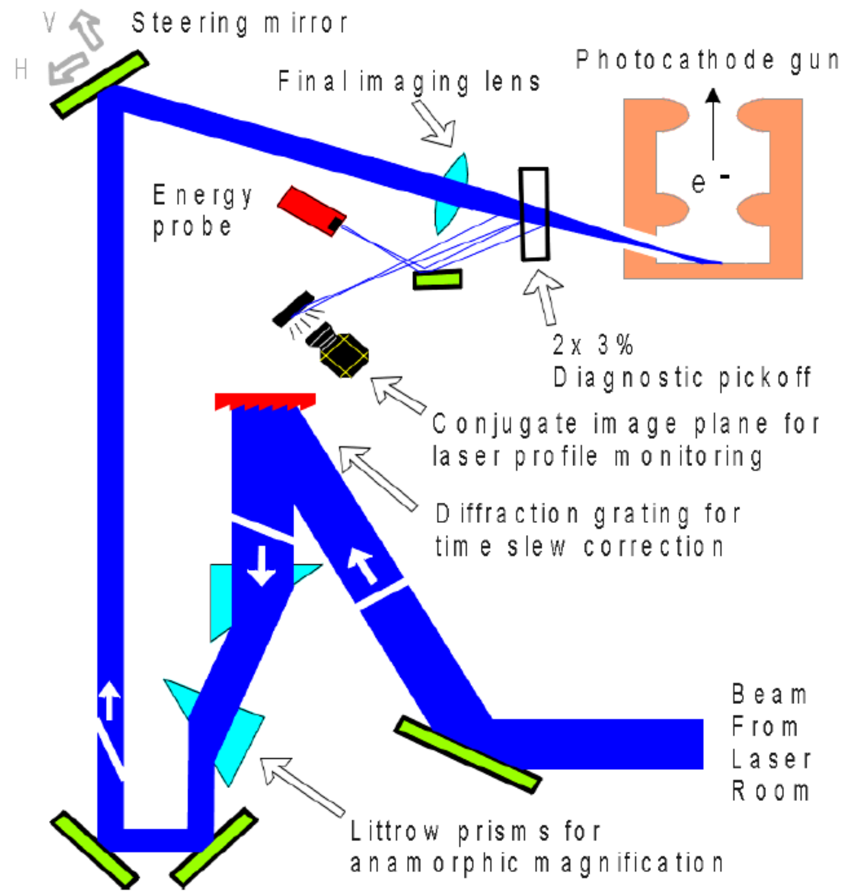
L. H. Yu,* L. DiMauro, A. Doyuran, W. S. Graves,† E. D. Johnson, R. Heese, S. Krinsky, H. Loos, J. B. Murphy, G. Rakowsky, J. Rose, T. Shaftan, B. Sheehy, J. Skaritka, X. J. Wang, and Z. Wu
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973, USA
(Received 25 March 2003; published 14 August 2003)

Why Photocathode RF Gun

- **6-D performance – smaller emittance and shorter bunch.**
- **Flexibility.**

But it bring more issues, ***mainly laser and cathode:***

- Stability
- Reliability
- Uniformity – QE, transverse and longitudinal distribution
- Jitters – position and **time**

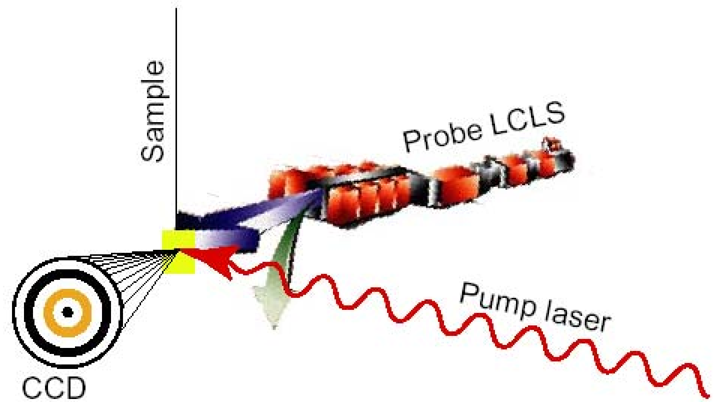


Timing jitter effects - Laser e^- beam (FEL) Interaction

$$\tau = \sqrt{\tau^2{}_{pump} + \tau^2{}_{FEL} + \tau^2{}_{jitter}}$$

$$\tau_{jitter} \prec \tau_{pump} \; or \; \tau_{FEL}$$

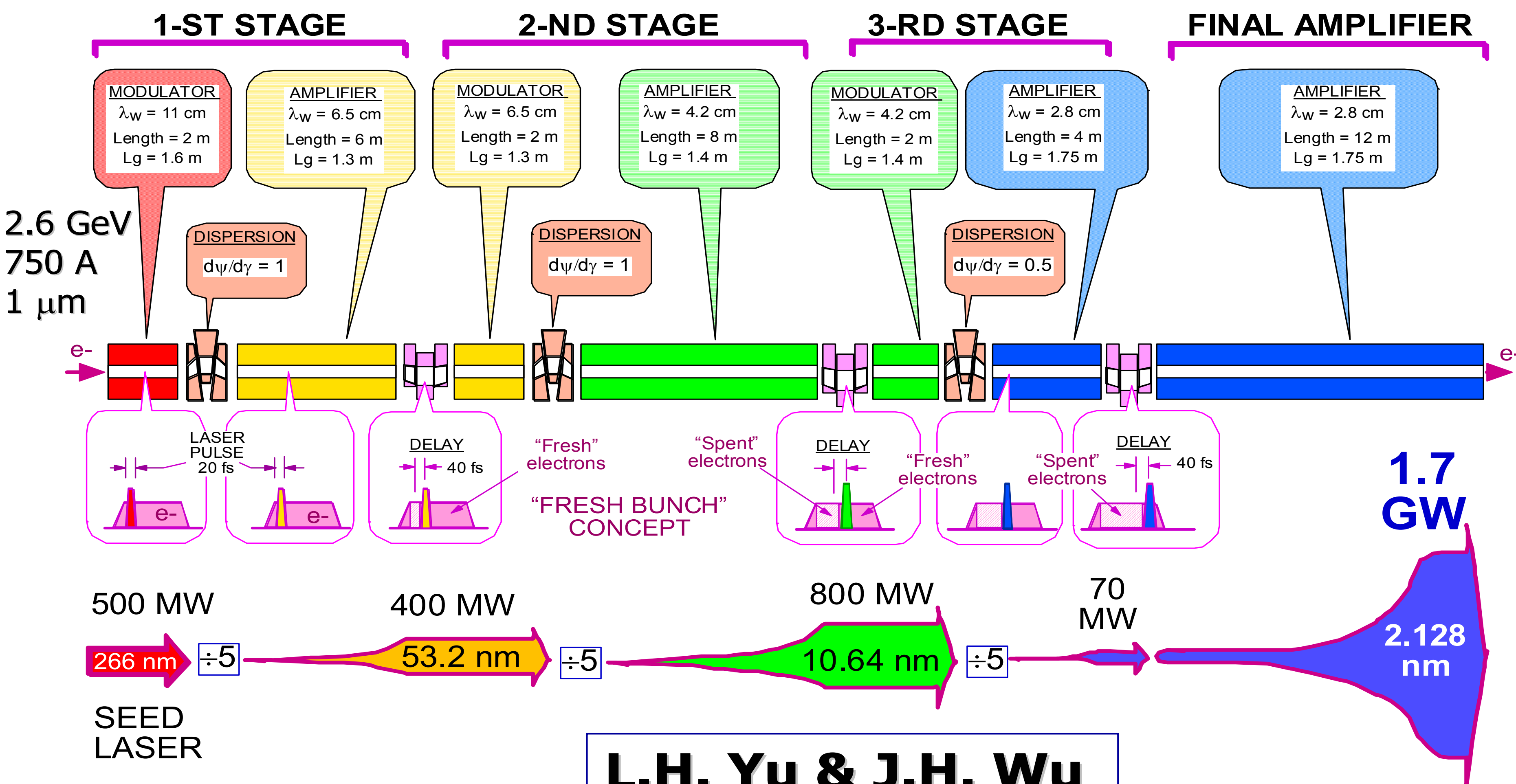
$$\tau \leq 100\, fs$$



The femtochemistry experiments use an ultrafast laser to initiate the process and the *LCLS* beam as a probe

Cascaded HGHG SXFEL: 20 Å, 20 fs

Soft X-Ray Free-Electron Laser



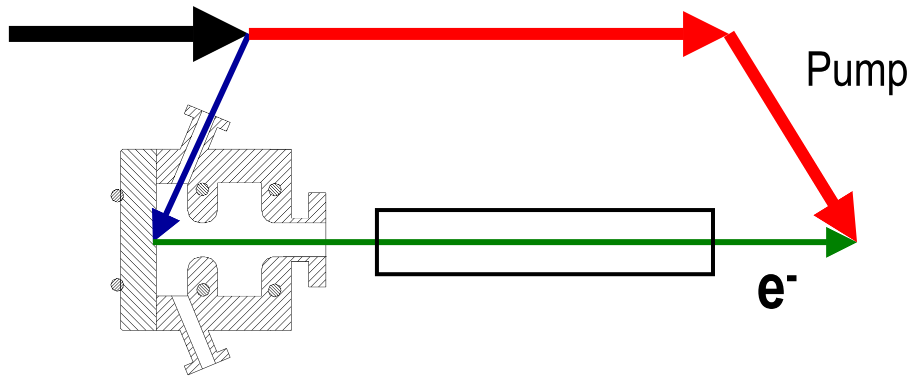
L.H. Yu & J.H. Wu

Brookhaven Science Associates
U.S. Department of Energy

Artwork by G. Rakowsky

BROOKHAVEN NATIONAL LABORATORY

The timing jitter between the two lasers *is* *the arriving time jitter of the electron beam relative to the pump laser*. Further more we can assume the photocathode RF gun laser and the pump laser is originated from the same laser, now the timing jitter is the traveling time jitter of the electron beam only



$$\delta t^2 = \sum \delta t^2{}_i$$

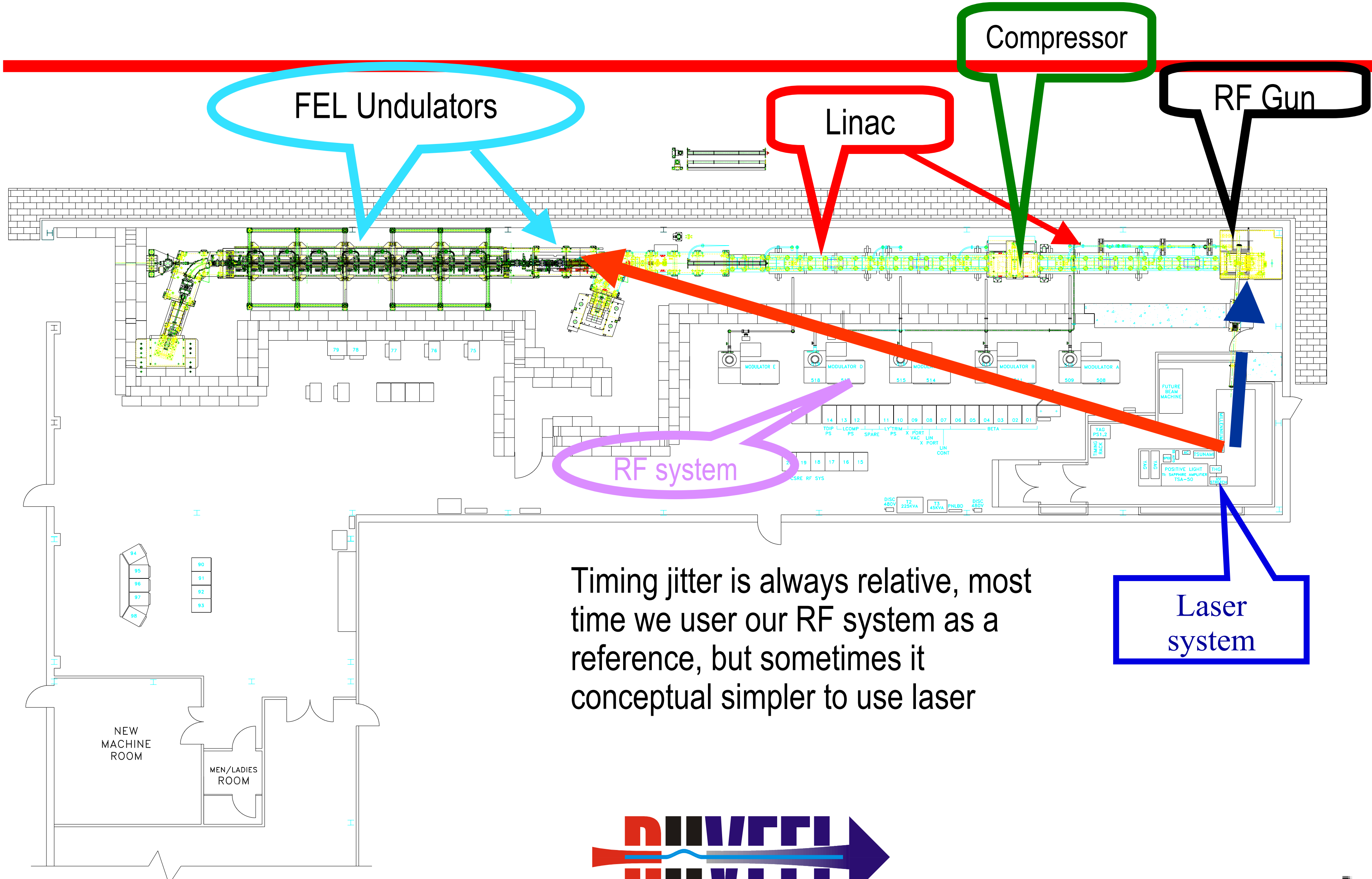
PHYSICAL REVIEW A, VOLUME 64, 021802(R)

Sub-10-femtosecond active synchronization of two passively mode-locked Ti:sapphire oscillators

Long-Sheng Ma,* Robert K. Shelton, Henry C. Kapteyn, Margaret M. Murnane, and Jun Ye†
JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440
(Received 30 November 2000; published 10 July 2001)

Two independent mode-locked femtosecond lasers are synchronized to an unprecedented precision. The rms timing jitter between the lasers is 4.3 fs, observed within a 160-Hz bandwidth over minutes. Multistage phase-locked loops help to preserve this ultrahigh timing resolution throughout the entire delay range between pulses (10 ns). We also demonstrate that the same level of synchronization can be achieved with two lasers at different repetition frequencies.

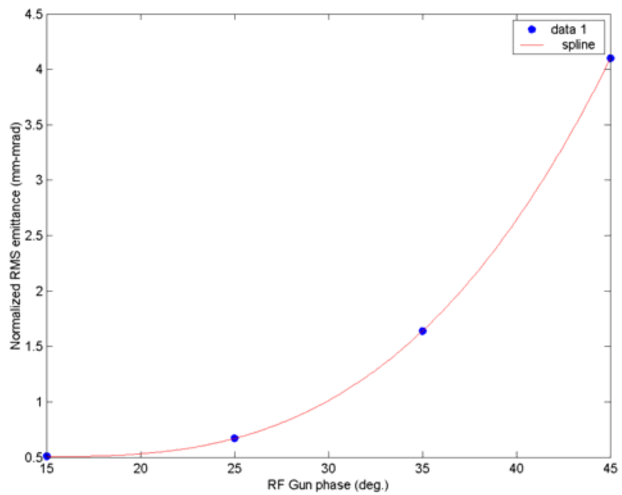
A Typical Photoinjector Based Linac System – BNL DUV-FEL

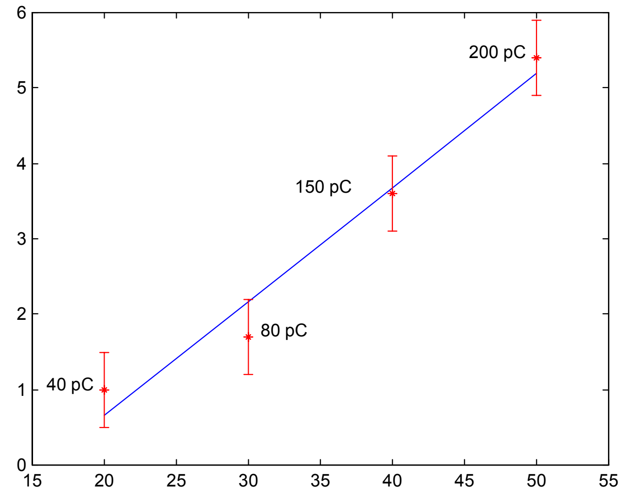


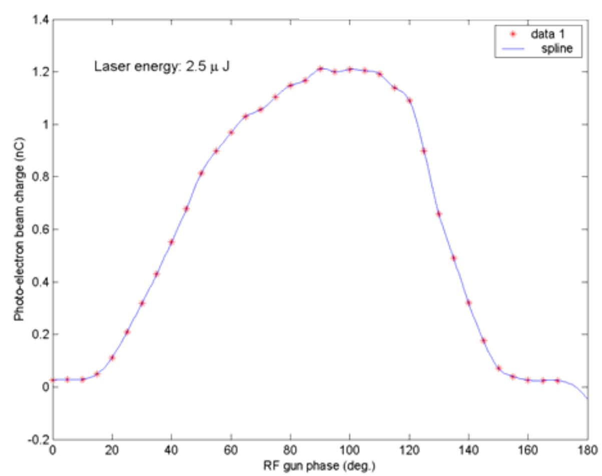
Timing jitter is always relative, most time we user our RF system as a reference, but sometimes it conceptual simpler to use laser

DUVFEL
Source Development Laboratory

Timing jitter effects – photocathode RF gun

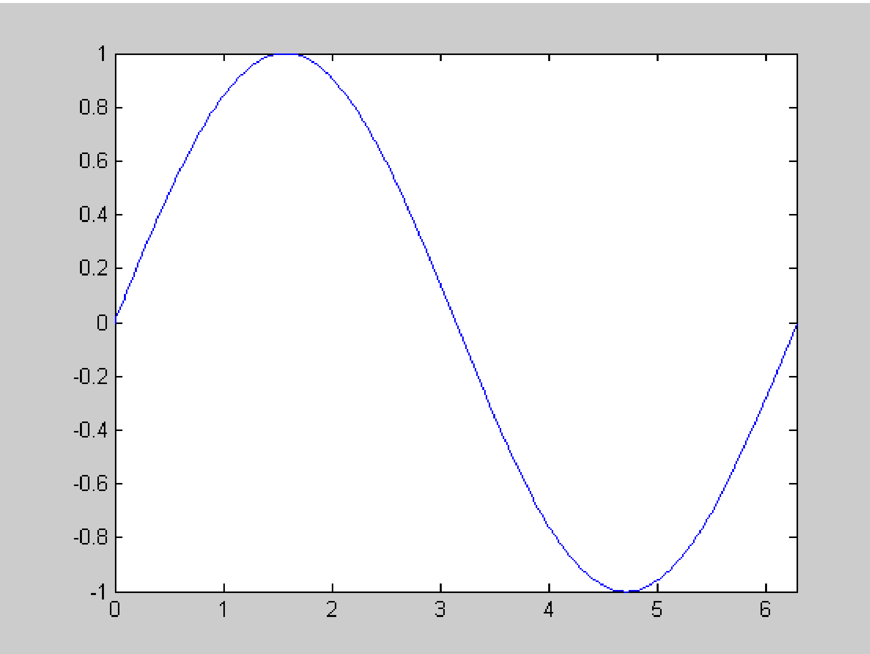


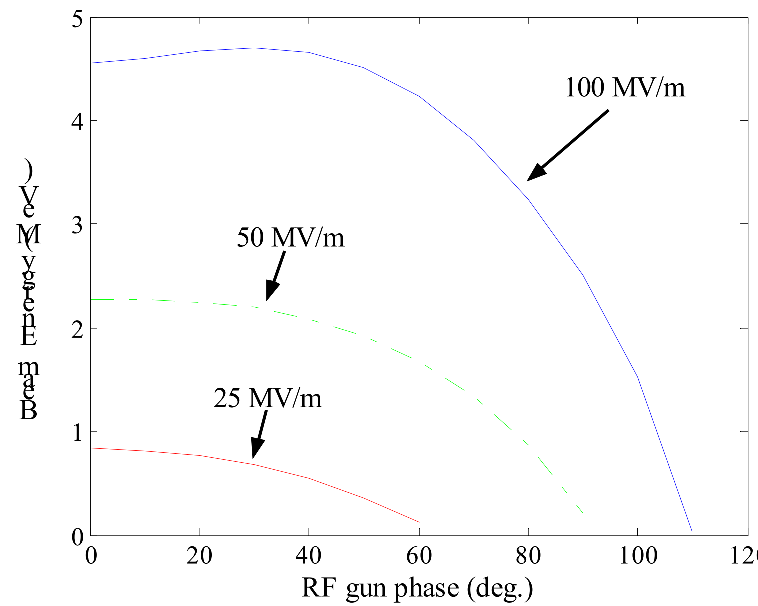




Jitter smaller < 200 fs (rms)

Timing Jitter Due to Energy Fluctuation



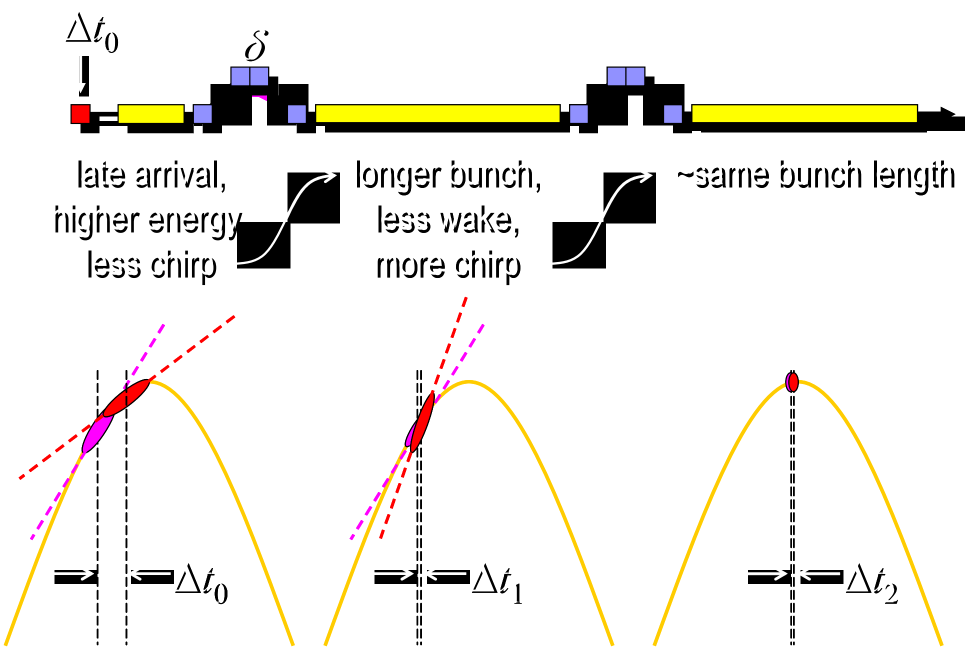


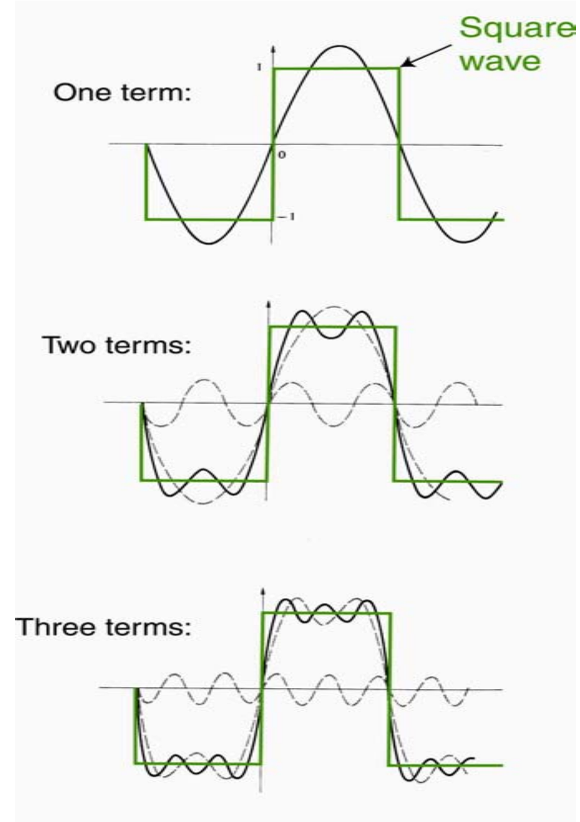
$$\delta t = \int \frac{E(z)}{\gamma^2(z)} \frac{d\ell}{\beta c}, \quad where\ E(z) = \frac{\delta\gamma}{\gamma}\ relative\ energy\ \ jitter$$

For 5 MeV beam through 1 meter, 10^{-3} energy jitter will lead to 30 fs arrive time jitter. Similar jitter will be generated inside the RF gun, RF gun energy stability better than 10^{-4} is required.

Timing jitter effects – Magnetic Chicane Compressor

Two-Stage Compression Used for Stability





System can be optimized for stability against timing & charge jitter

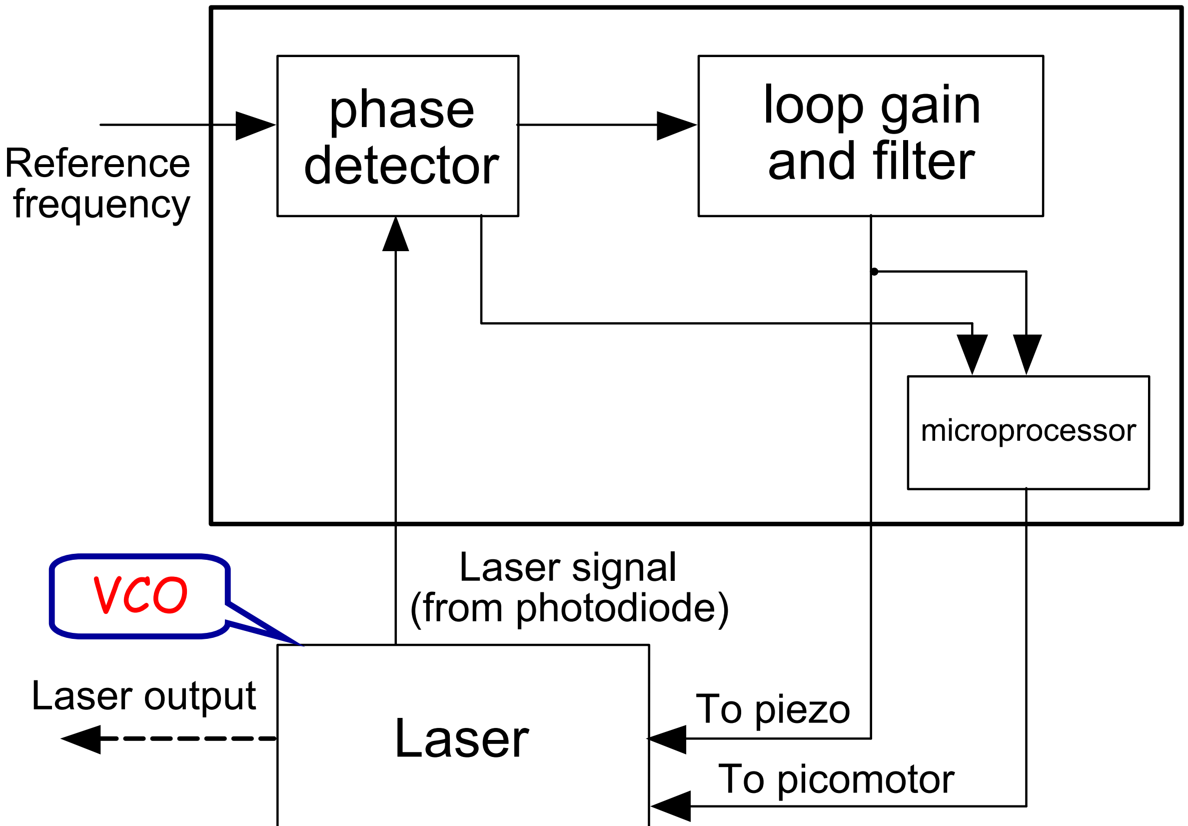
bunch length stability with RF phase jitter…

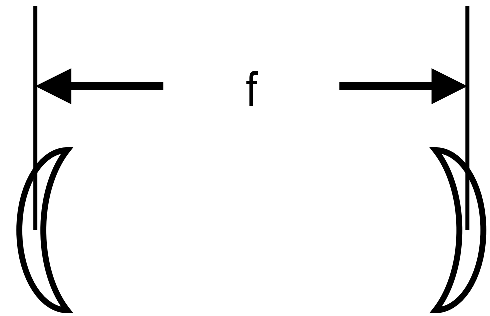
T. Raubenheimer

$$\frac{\Delta\sigma_z}{\sigma_z} \approx -\left(\frac{\sigma_{z0}}{\sigma_z} \mp 1\right)\Delta\varphi\cot(\varphi) \quad \Rightarrow \quad \frac{\sigma_{z0}}{\sigma_z} = 40: \quad 25\%\ \text{jitter} / 0.1\ \text{psec} \quad @ -15^\circ$$

P. Emma of SLAC

Timing Jitter Reduction
RF and Laser Synchronization



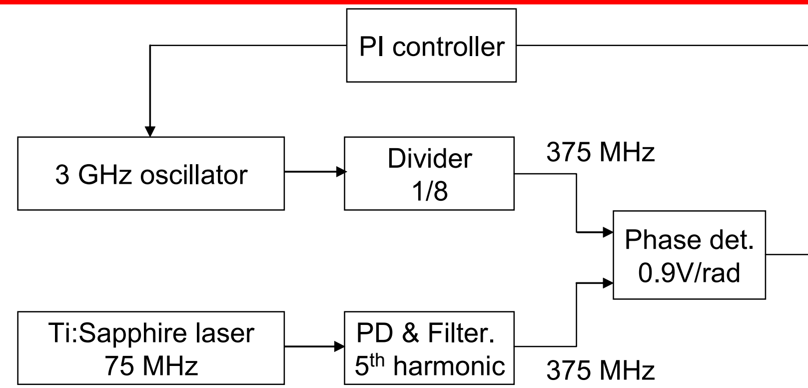


IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 25, NO. 4, APRIL 1989

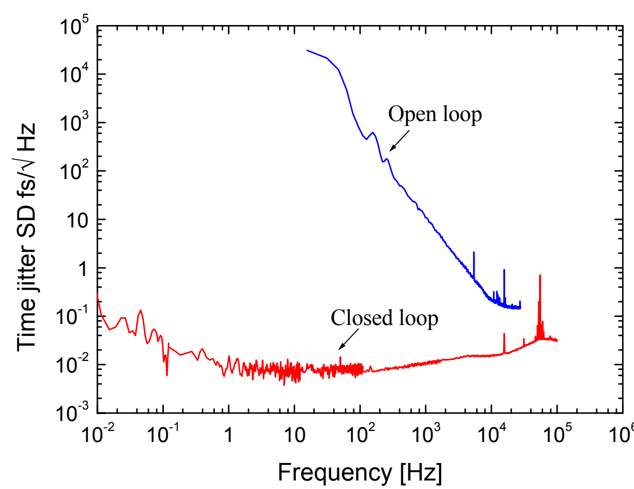
Subpicosecond Laser Timing Stabilization

MARK J. W. RODWELL, DAVID M. BLOOM, FELLOW, IEEE, AND
KURT J. WEINGARTEN, MEMBER, IEEE

Other Options



- Laser oscillator as the RF source.
- RF oscillator driven by the phase error.



Submitted to Optic Letters

Goal : $\sigma_t < 1$ ps

Achieved : $\sigma_t = 18$ fs (50 mHz–100 kHz)

TUE

Is Ti:Sap Laser a right Choice?

Noise characterization of an all-solid-state mirror-dispersion-controlled 10-fs Ti:sapphire laser

Makoto Aoyama, Koichi Yamakawa [1]

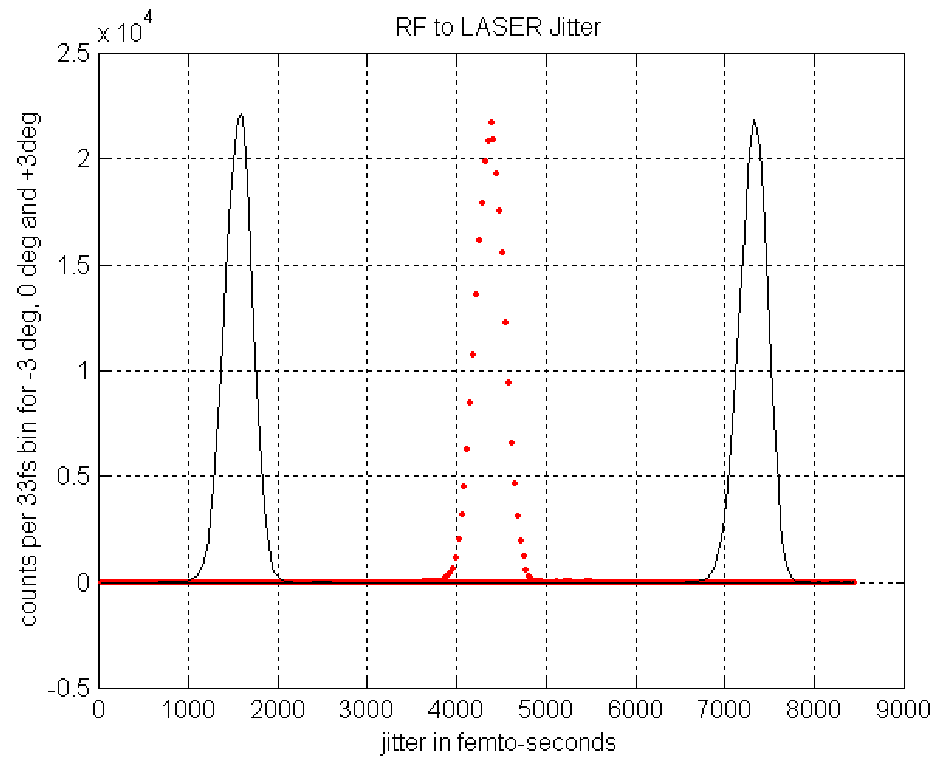
Advanced Photon Research Center, KANSAI Research Establishment, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-11, Japan

Received 2 January 1997; revised 14 March 1997; accepted 9 April 1997

Abstract

We characterized the phase and amplitude noise of a mirror-dispersion-controlled 10-fs Ti:sapphire laser pumped by a frequency-doubled cw diode-pumped $Nd:YVO_4$ laser and compared with these of the Ti:sapphire laser pumped by an Ar-ion laser. The rms timing jitters and rms amplitude noise for the all-solid-state and Ar-ion laser pumped Ti:sapphire lasers are calculated to be 0.31 ps rms and 0.71 ps rms and 0.15% rms and 0.32% rms, in the frequency range from 20 kHz to 400 kHz, respectively. The phase and amplitude noise characteristics of the Ti:sapphire laser were greatly improved by using the diode-pumped solid state laser as a pump source. © 1997 Elsevier Science B.V.

BNL DUV-FEL Laser Oscillator Timing Jitter Measurement

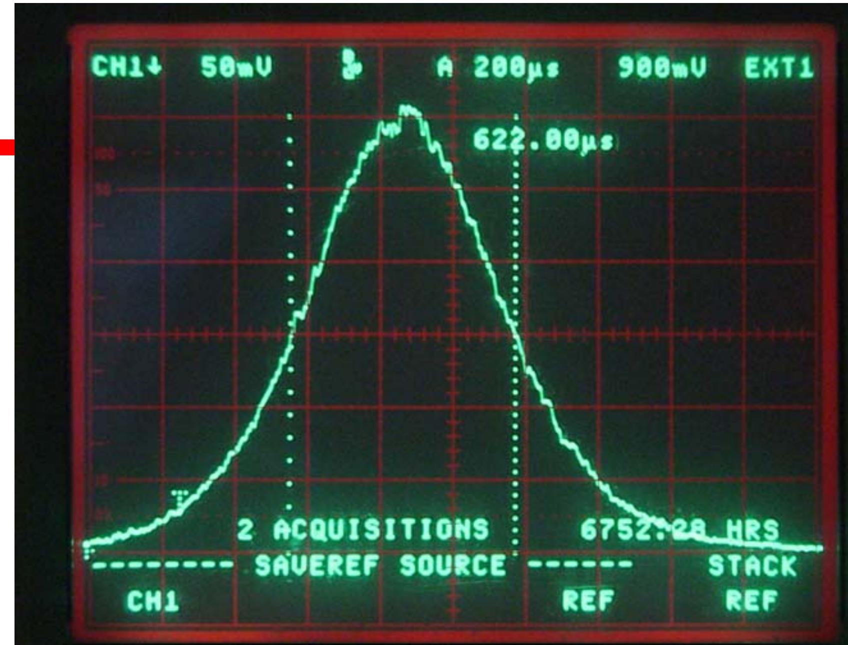


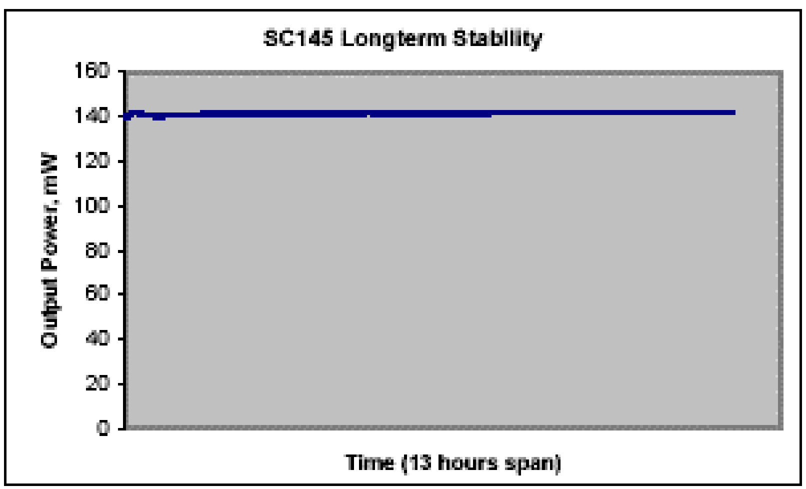
J. Rose of BNL

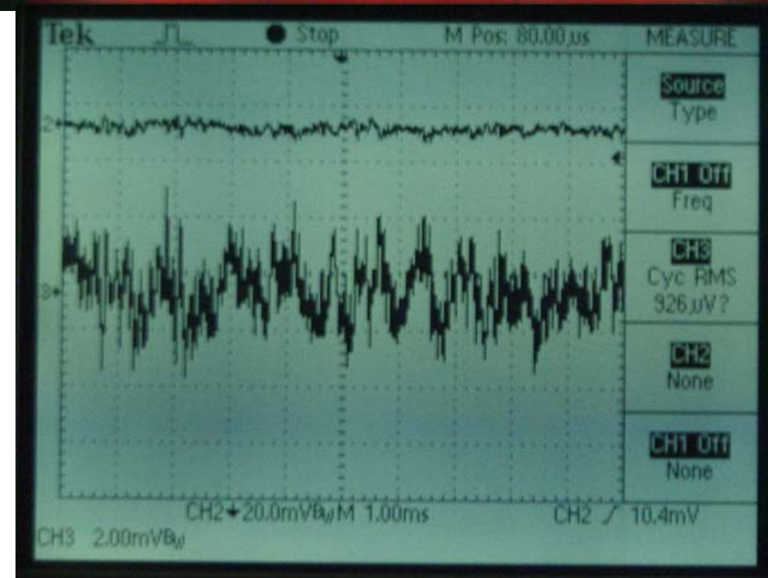
200 fs Yb:glass oscillator

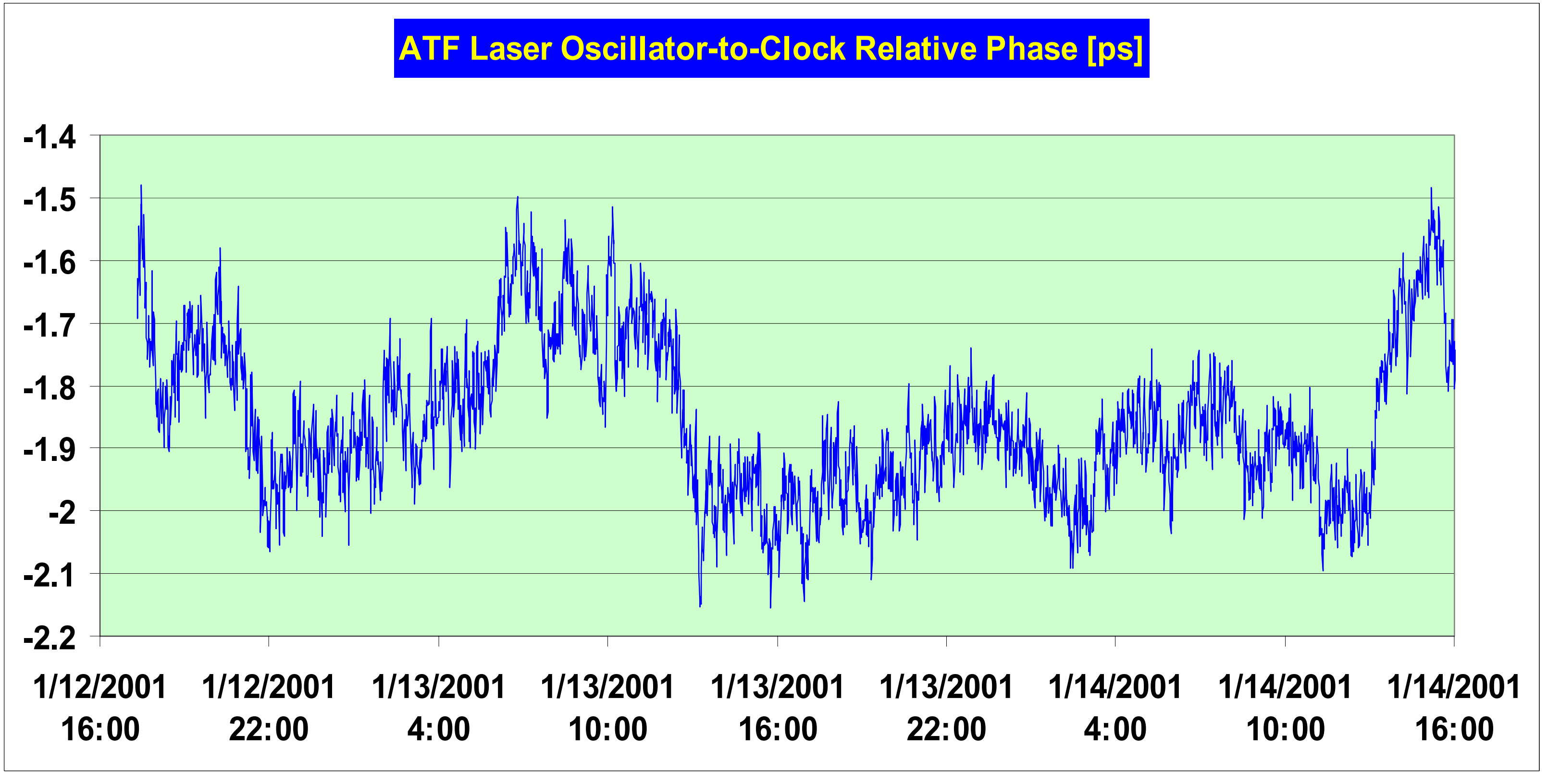
λ(um)	P (mW)	L(FWHM, fs)
1.051	136	150
1.047	117	177

Timing jitter: 200fs (FW, detector limited)



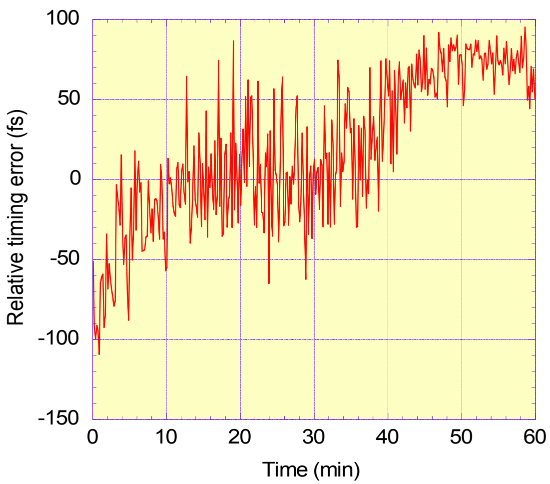




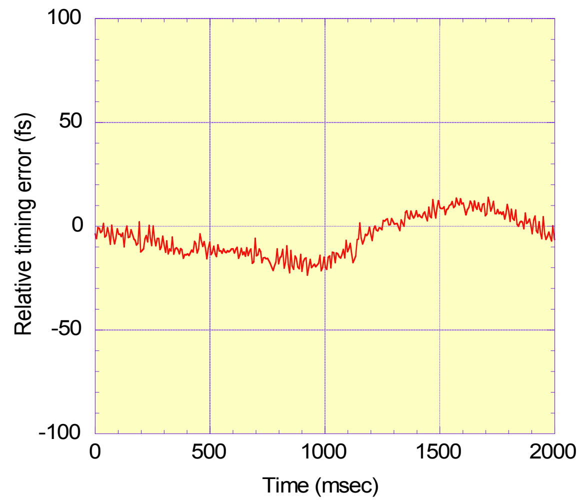


ATF Laser Oscillator-to-Clock Relative Phase [ps]
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
-2.1
-2.2
1/12/2001 16:00
1/12/2001 22:00
1/13/2001 4:00
1/13/2001 10:00
1/13/2001 16:00
1/13/2001 22:00
1/14/2001 4:00
1/14/2001 10:00
1/14/2001 16:00

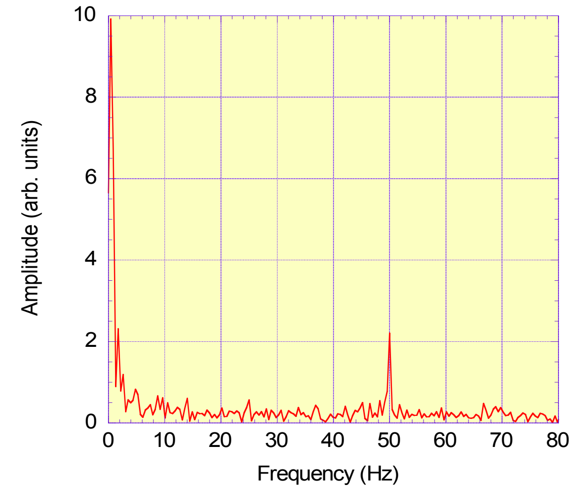
Measurement of timing fluctuation of the amplified pulses



(a) Long term drift



(b) Short term fluctuation

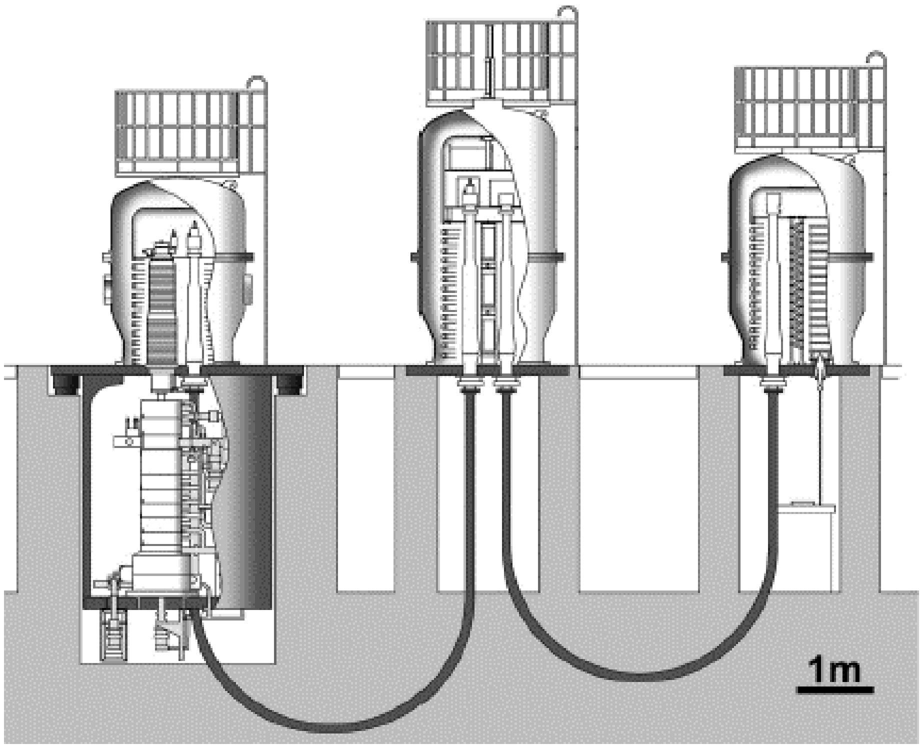


(c) Fourier transform of (b)

Long term (one hour) drift was less than 200 fs.
Short term (several seconds) fluctuation was about 10 fs.

Ultra-Stable H.V. Power Supply for Klystron

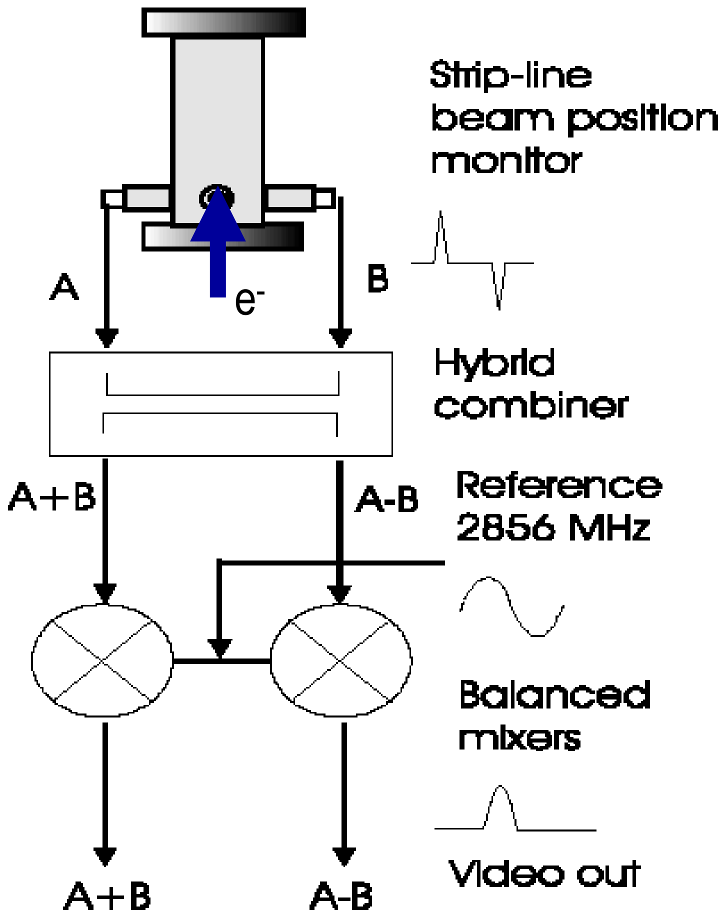
$$\Delta E \propto L\sqrt{P} \propto CV^{5/4}$$

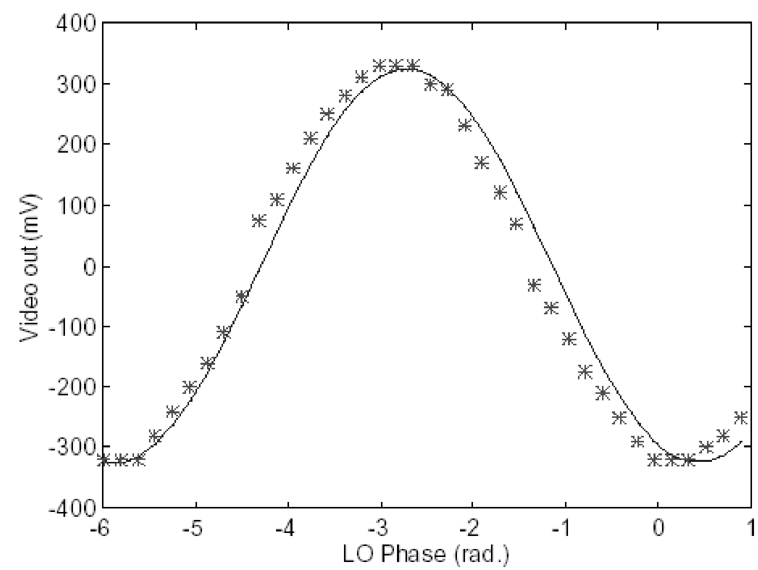


1 MV Electron Microscope.

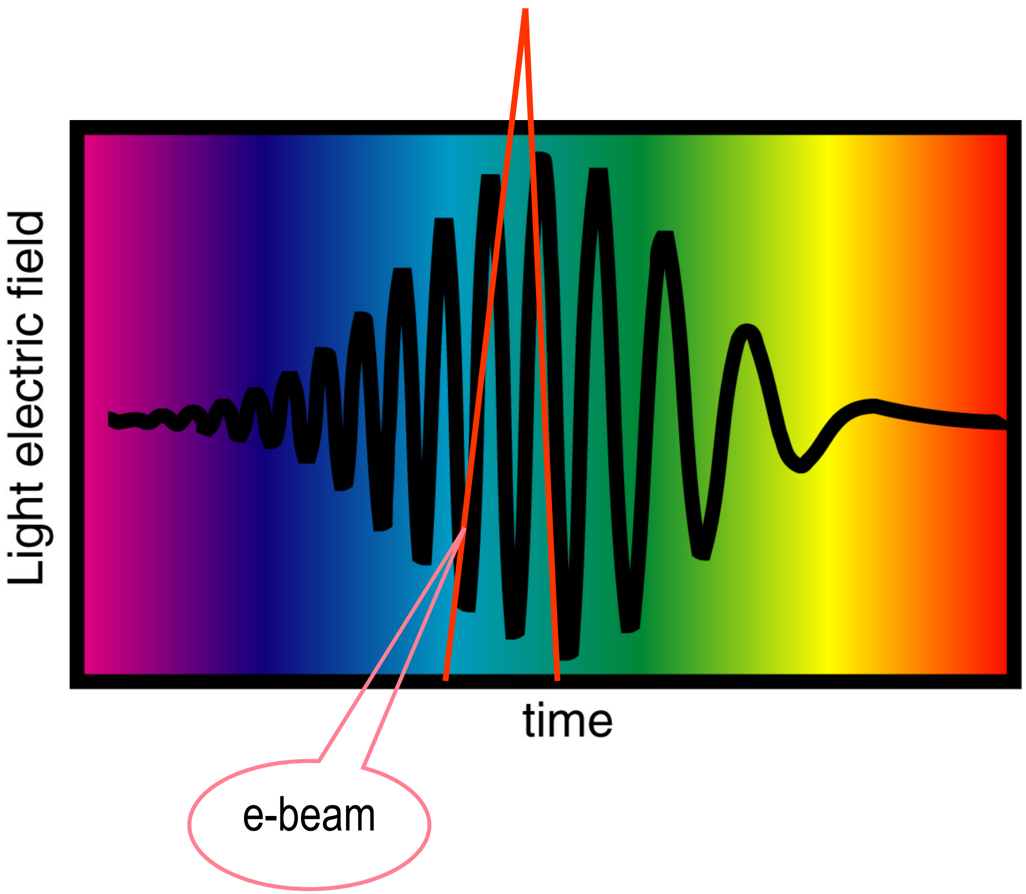
- Direct DC H.V. Charging power supply.
- **Solid State Modulator.**

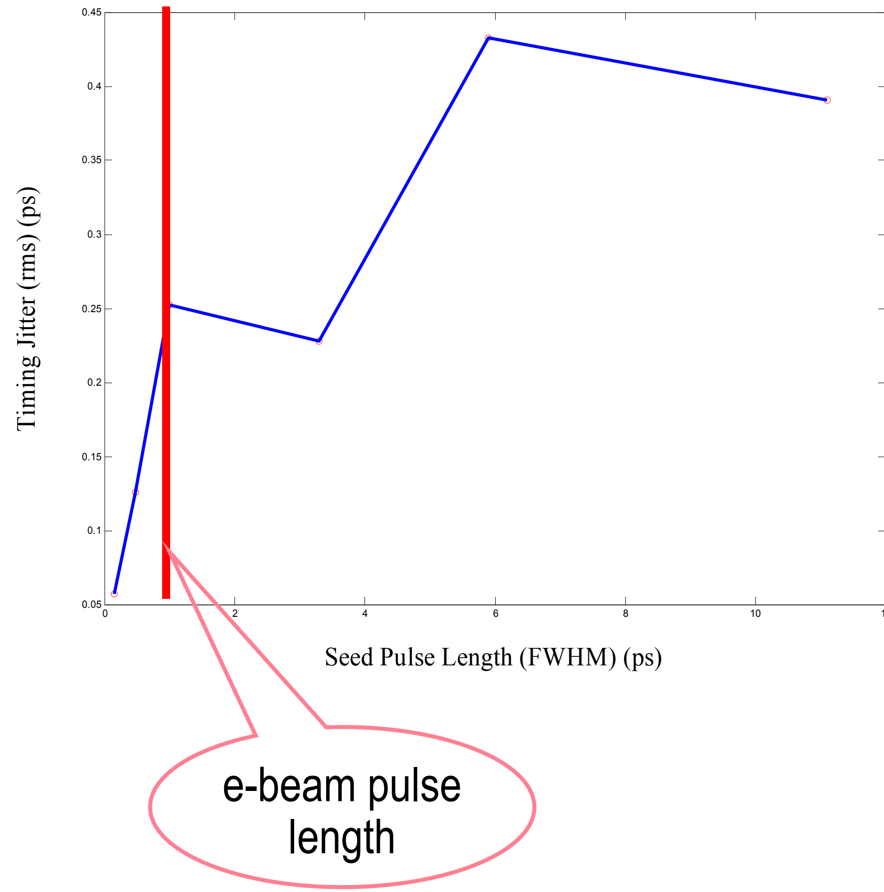
Jitter Measurement Techniques – RF



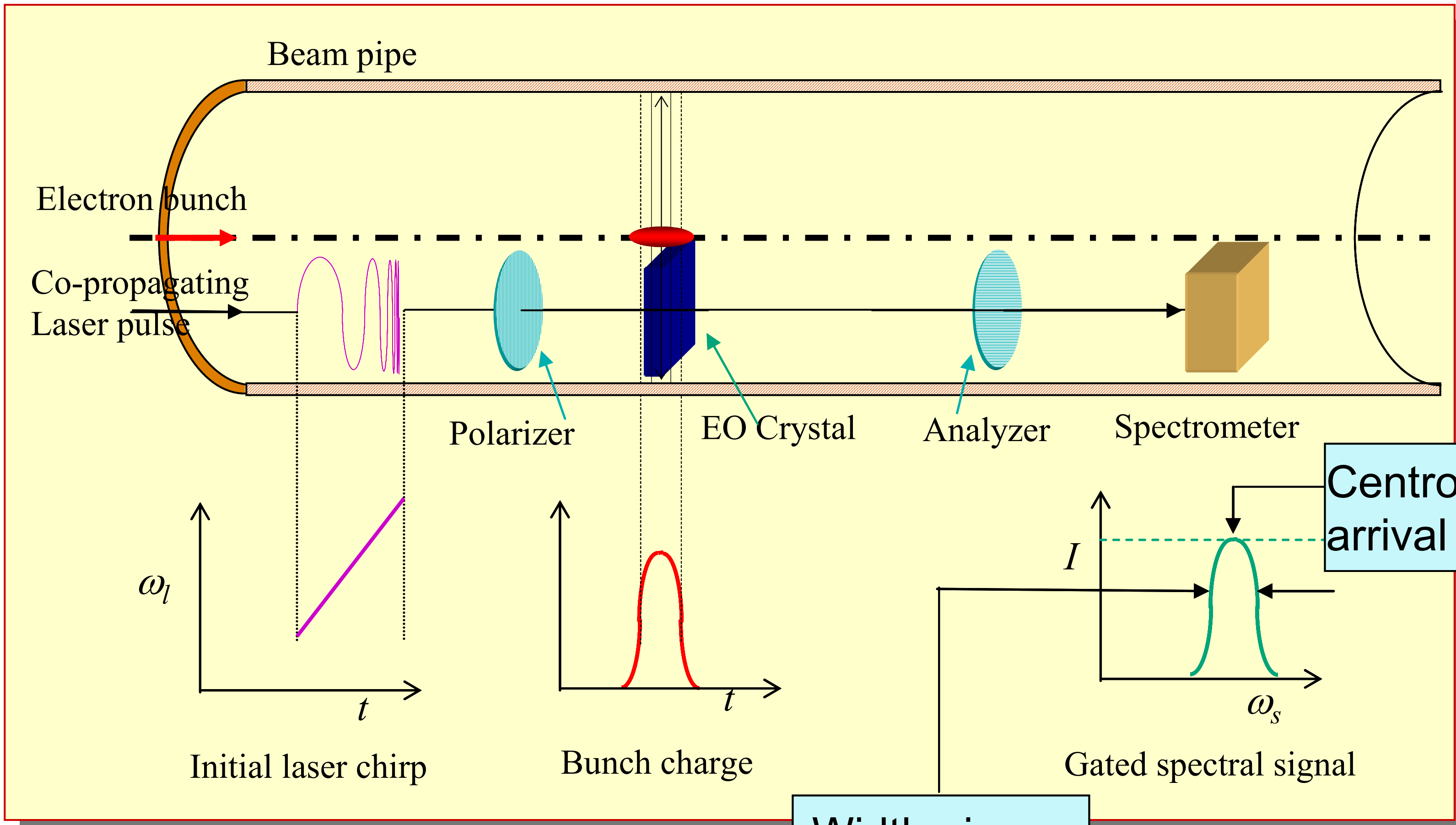


Jitter Measurement Technique Based on HGHG





Experimental results: H. Loos *et al*, "Electro-Optical Longitudinal Electron Bunch Shape Diagnostic at the DUV-FEL", **Tu-P-51.**



Centroid gives arrival time

Width gives bunch length

P. Krejcik of SLAC

Summary:

We have shown that, it is possible to realize sub-100fs timing jitter if:

- Proper laser technology and environment.
- Improve the RF power amplitude and phase stability of the photocathode RF gun – such as use DC modulator.
- Good jitter diagnostics.

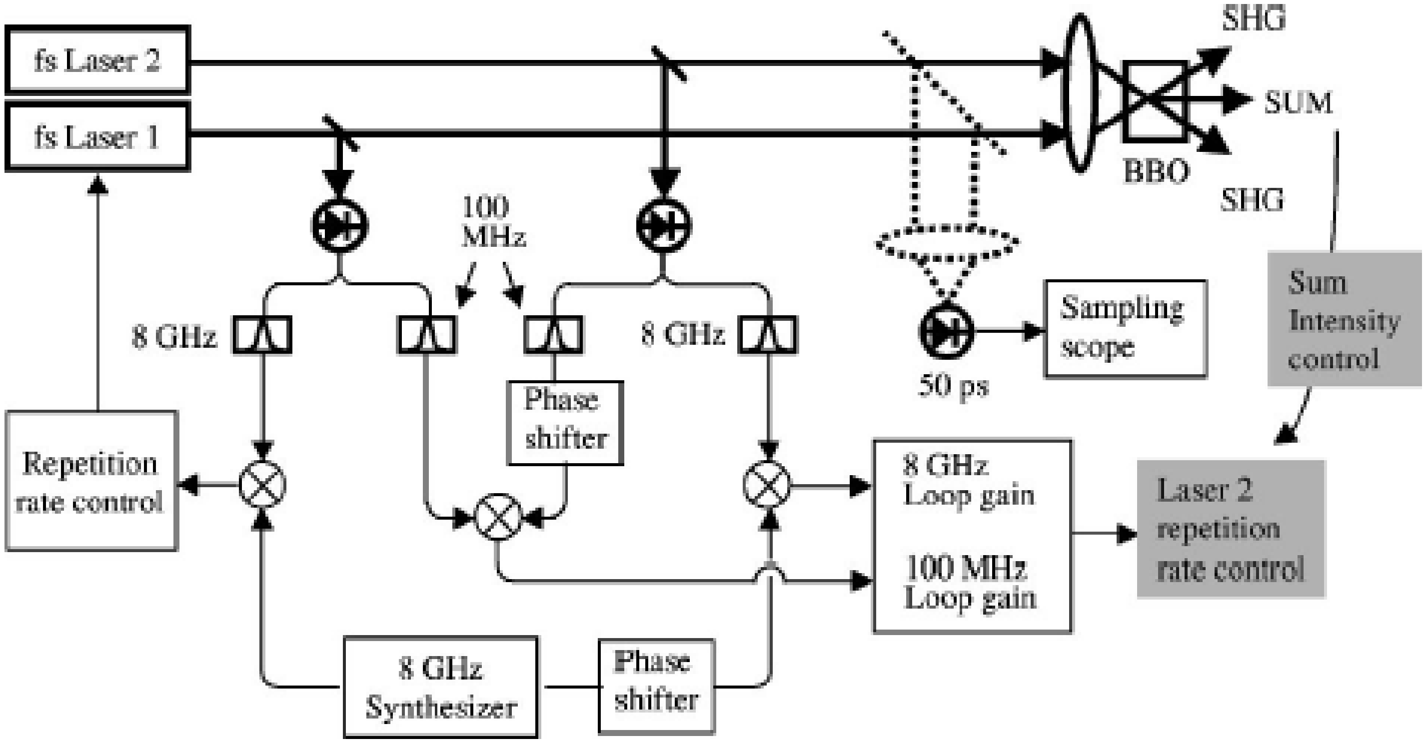


FIG. 1. Experimental setup for timing synchronization of two femtosecond lasers. The four phase-locked loops for synchronization are shown, along with the signal analysis scheme.