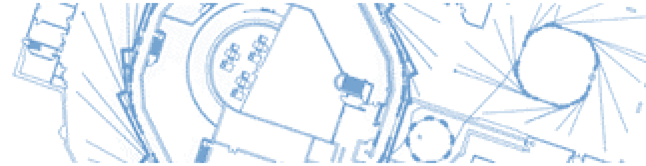
NSLS
NATIONAL SYNCHROTRON LIGHT SOURCE



What I learned From 15 Years of RF Gun Operation at the BNL

Stability and Reliability

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Brookhaven National Laboratory
Upton, NY 11973, USA

Presented at the ANL theory Institute On Production of brightness Beams
September 23, 2003

Acknowledgement

I would like to thank many colleague who have educated me over many years on various subjects I mentioned here,

BNL: M. Babzien, K. Batchelor, I. Ben-Zvi, A. Doyuran, J. Fisher, W. Graves, H. Loss, J. Murphy, T. Rao, J. Rose, B. Sheehy, J. Sheen, Z. Wu, V. Yakimenko and L.H. Yu

ANL: S. Biedron, M. Conde, W. Gai, J. Lewellen, S. Milton, J. Power

SLAC: R. Miller, D.T. Palmer

Japan: A. Endo, K. Kobayashi, F. Sakai, J. Urakawa, Uesaka and M. Washio

And Many others. Thank you!

Outline

- Introduction – What are the performance and Applications
- Vacuum and QE do Matter.
- 6-D Performance Optimization
- Timing Jitter – What is required?
- Summary – We did better than theory!

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)

Introduction

All the FEL reach saturation does not test the limit of the emittance performance:

1. LEUTL and TTF I < 6-10 mm-mrad
2. VISA <2.0 - 2.5 mm-mrad
3. DUV-FEL < 5 mm-mra

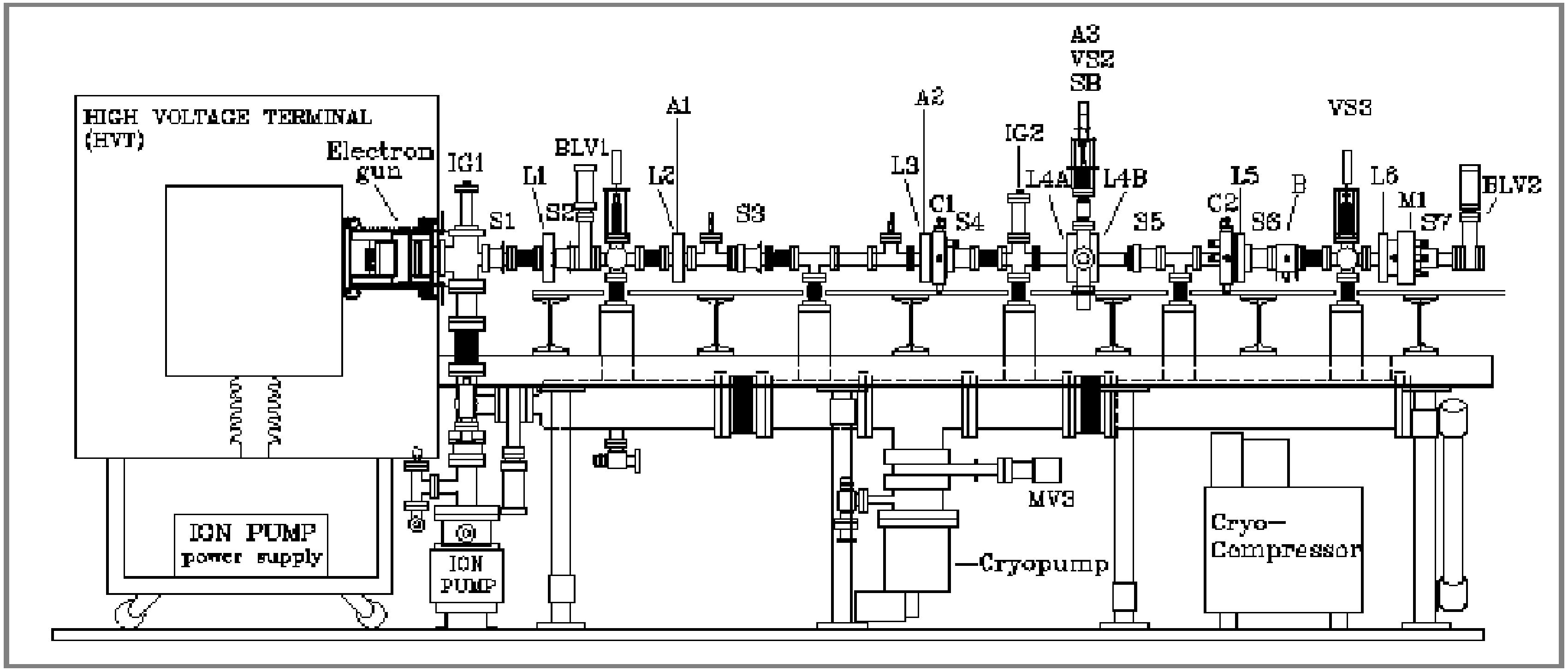
Does Any Physics Experiment Test the limit:

1. Laser Compton Scattering < 2 mm-mrad
2. IFEL Micro-bunching - Stella Experiment < 1-2 mm-mrad

Introduction - Applications

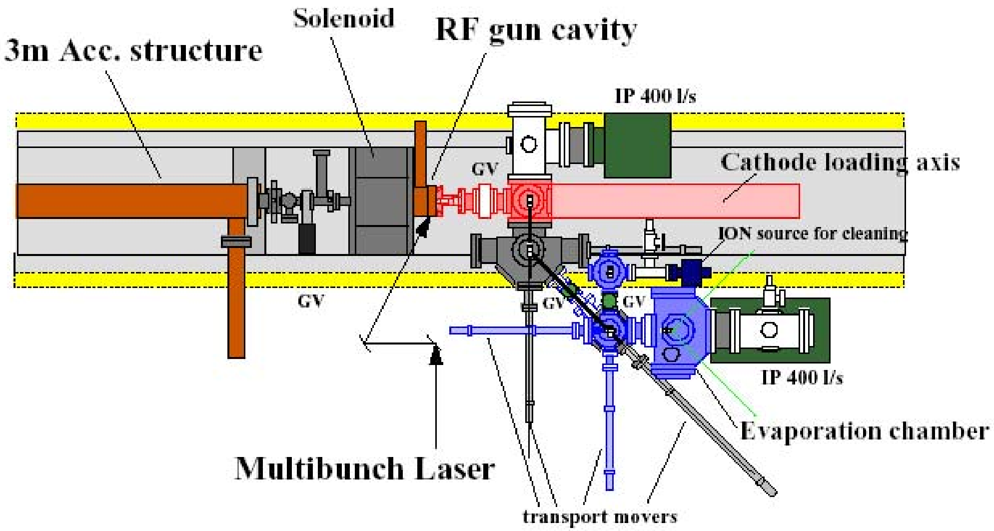
- Injector for Storage Ring ~ 70
- Pico Femto Second high-brightness electron beam on the table
- Other applications – femtosecond electron microscope

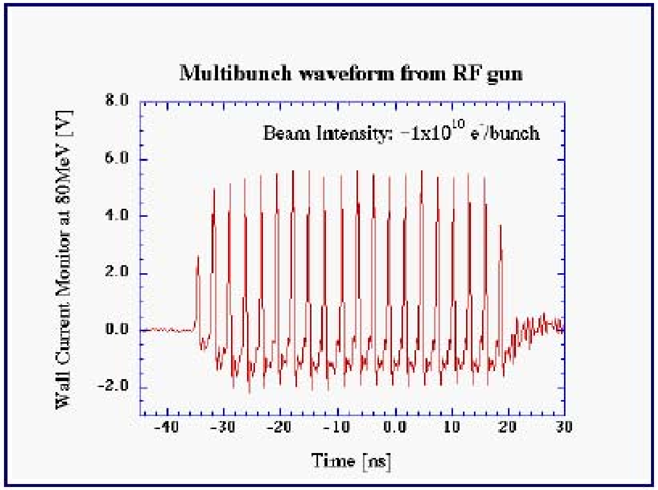
- Thermionic Electron Gun [100keV ($\beta=v/c=0.56$)]
- Chopper - Buncher System
- Capture Section (β-graded) [1.5 MeV ($\beta=0.95$)]
- Pre-Accelerator (few MeV, β~1)
- Booster (4 m long → 10.5 MeV)



Multibunch photo-cathode RF gun in ATF

for better Multibunch injection into DR





BNL type RF gun + CsTe cathode

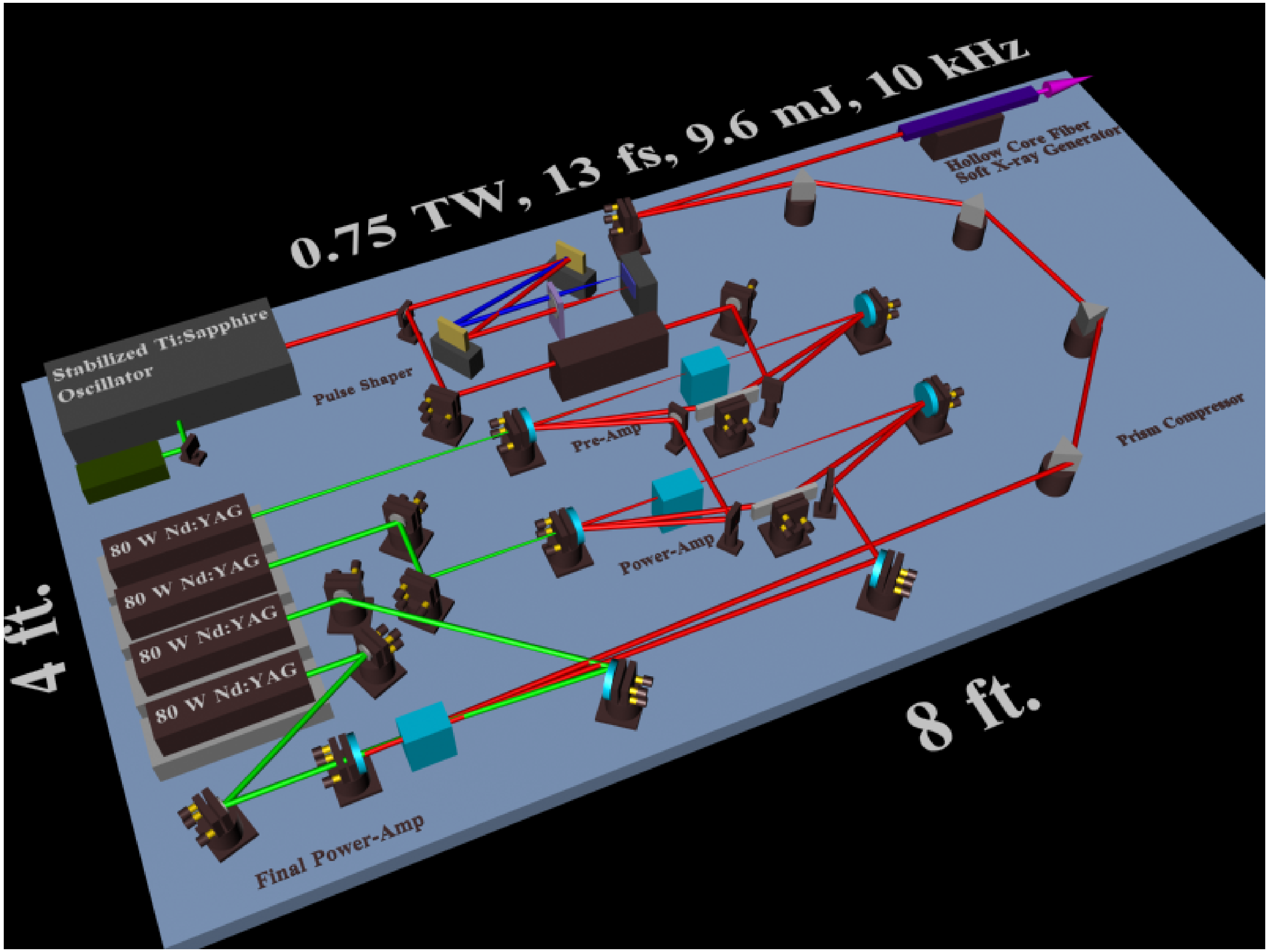
Load-lock system for CsTe

357MHz , 266nm, 20 bunch Laser

at 80MeV
Intensity : ~1E10 /bunch
bunch length : ~7ps
Normalized emittance : 28E-6 m.rad

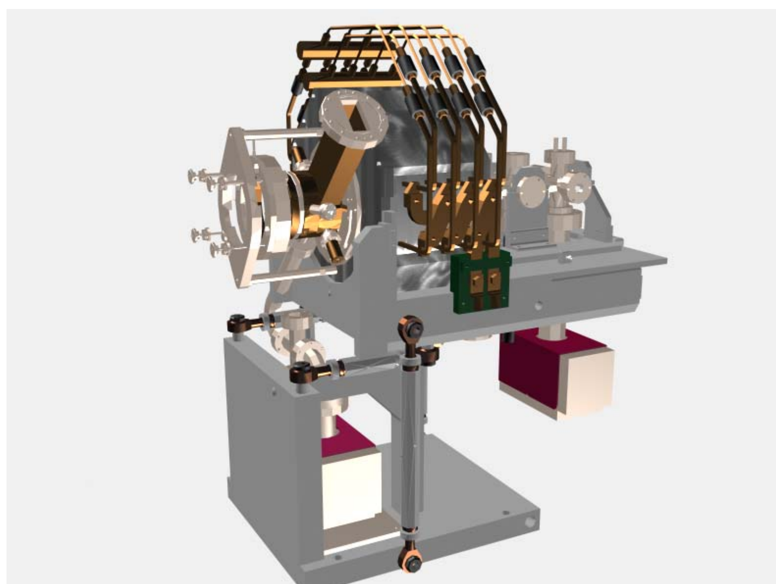
Oct. 2 2002

T^3 Laser System – revolutionize the high power laser applications



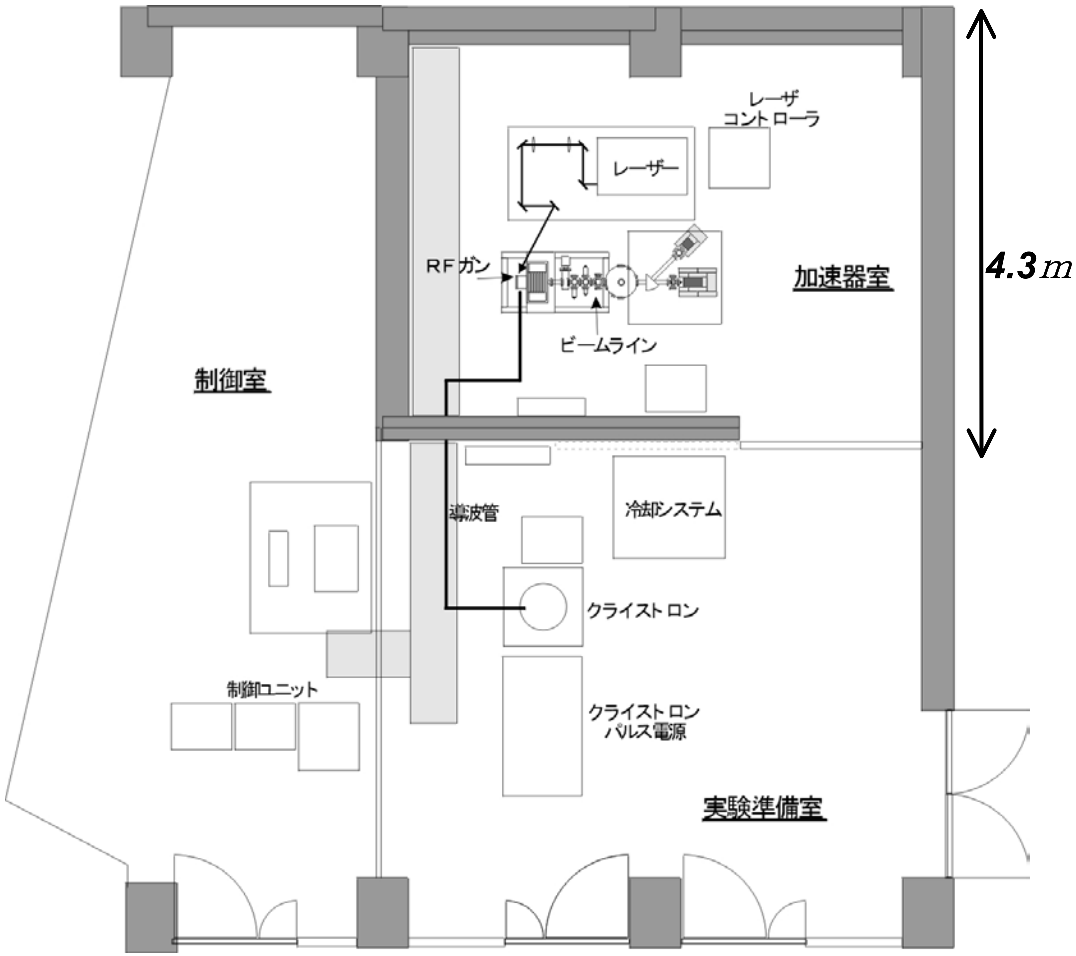
Phtoinjector for T^2 (Table Top or 2 tables) system

- Beam Physics
- Soft X-ray Source
- Coherent THz source
- Pulse Radiolysis



Femto-second Electron Diffraction

Experimental room

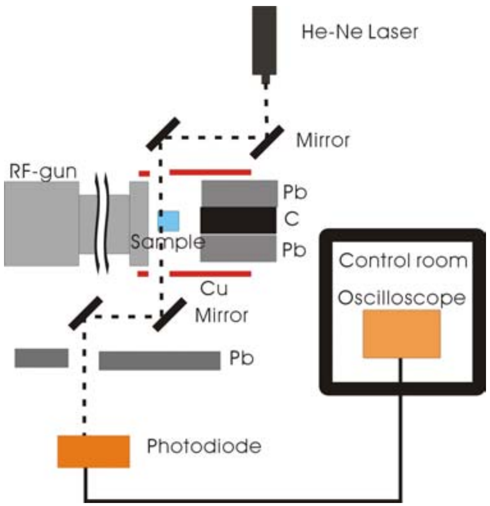


Pulse Radiolysis Experiment

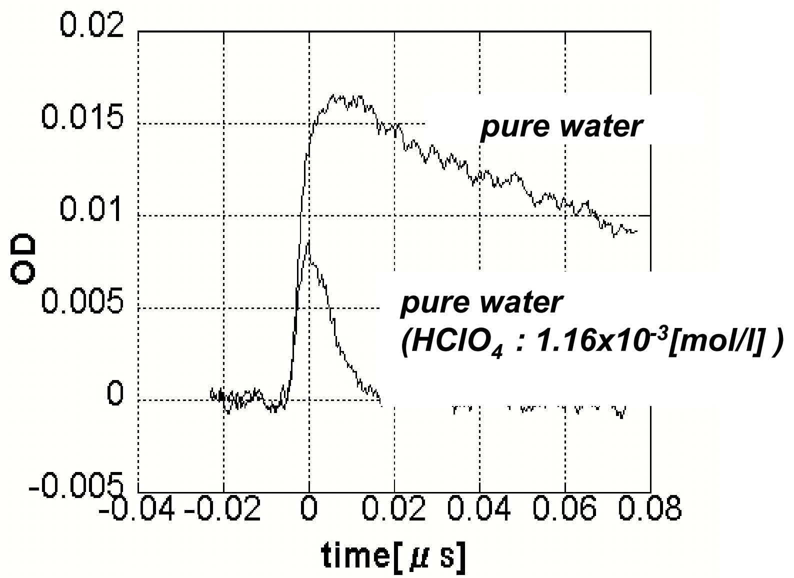
•Our system is based on pomp-and-probe pulse radiolysis method. Electron beam used as irradiation source is originally 10ps single pulse. Laser light, which is CW laser light or pico-second laser pulse, is used as a probe .

•Absorption measurement using CW laser light (He-Ne: 630nm

Setup



Time profile of hydrated electron



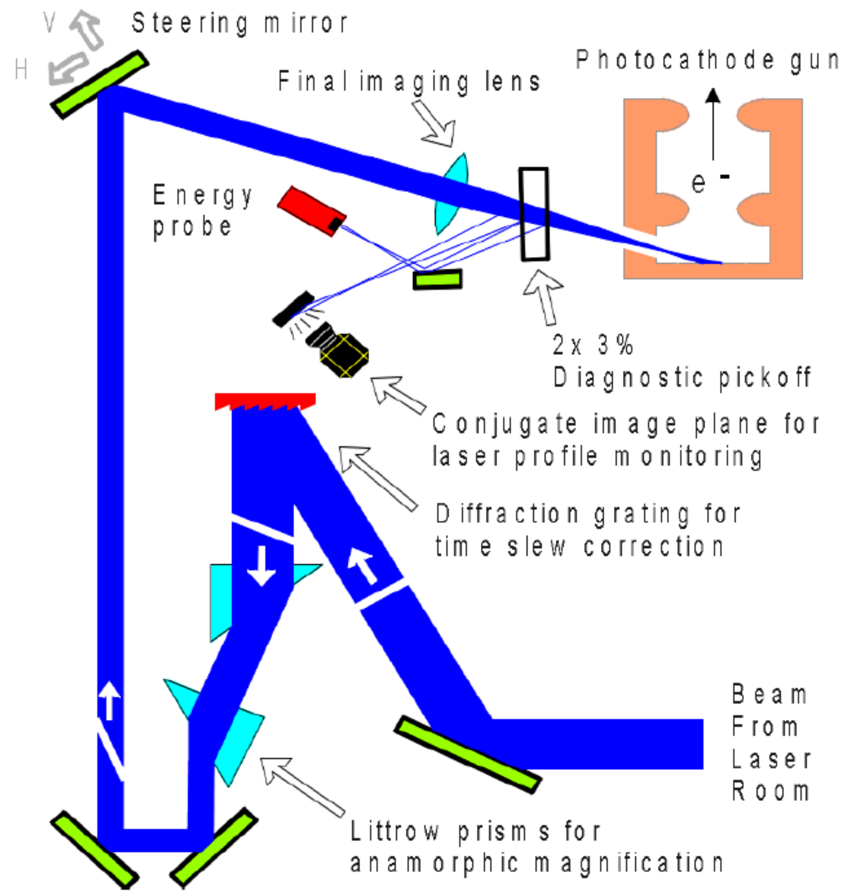
•Now, we are developing a stroboscopic pulse radiolysis system using 10 ps white-light.

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**



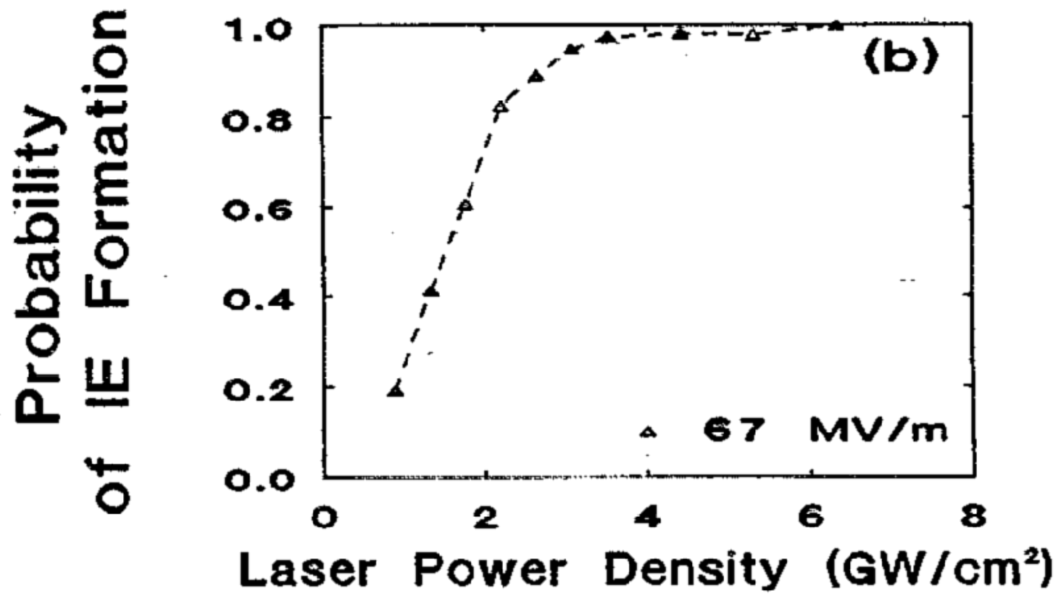
Vacuum and QE Do Matter

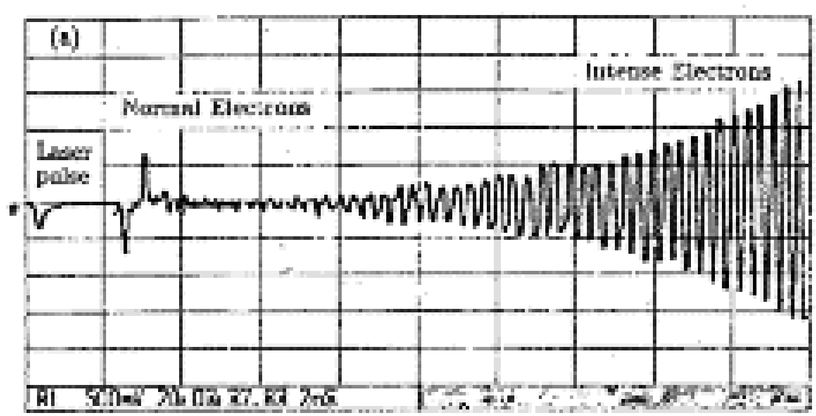
(at Room Temperature)

Pressure (Torr)	Molecular Density (molec./cm^3)	Molecular Incidence (molec./cm^2·sec)	Mean Free Path (cm)	Monolayer Formation Time (sec)
760	2.49×10^{19}	2.87×10^{23}	3.9×10^{-6}	1.7×10^{-9}
1	3.25×10^{16}	3.78×10^{20}	5.1×10^{-3}	2.2×10^{-6}
10^{-3}	3.25×10^{13}	3.78×10^{17}	5.1	2.2×10^{-3}
10^{-6}	3.25×10^{10}	3.78×10^{14}	5.1×10^{3}	2.2×10^{0}
10^{-9}	3.25×10^{7}	3.78×10^{11}	5.1×10^{6}	2.2×10^{3} (37 min)
10^{-12}	3.25×10^{4}	3.78×10^{8}	5.1×10^{9}	2.2×10^{6} (25.5 days)

Laser-Induced Explosive Emission

(X.J. Wang *et al*, J. Appl. Phys. 72(3), 888-894 (1992))





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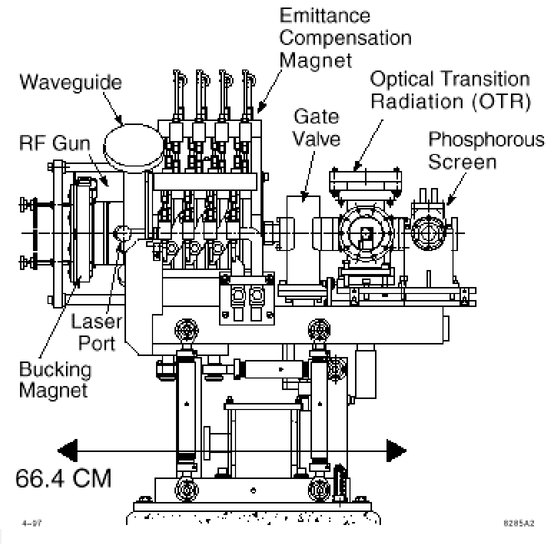
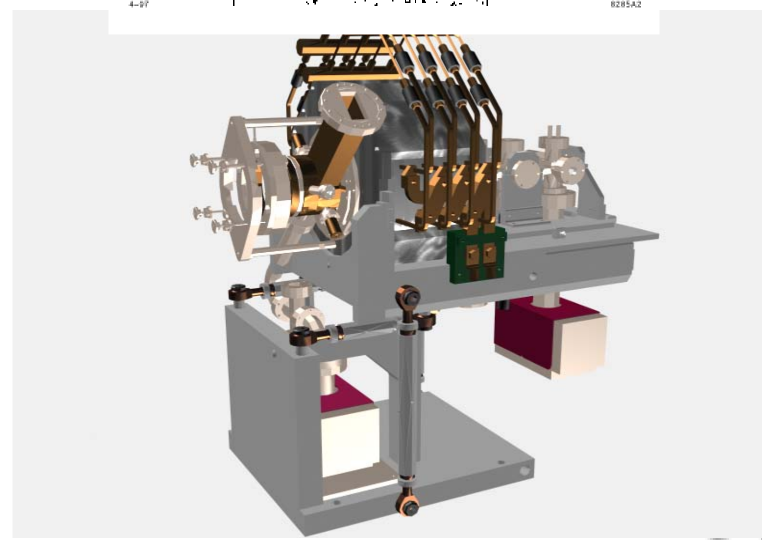
Photocathode RF Gun Injection System

- Photocathode RF gun injection system:

1. RF gun.
2. Solenoid Magnet.
3. RF gun associate beam diagnostics.
4. Laser system and optics.
5. Cathode technology
6. Operating principle

Stability and Reliability





What We would like Photoinjector do

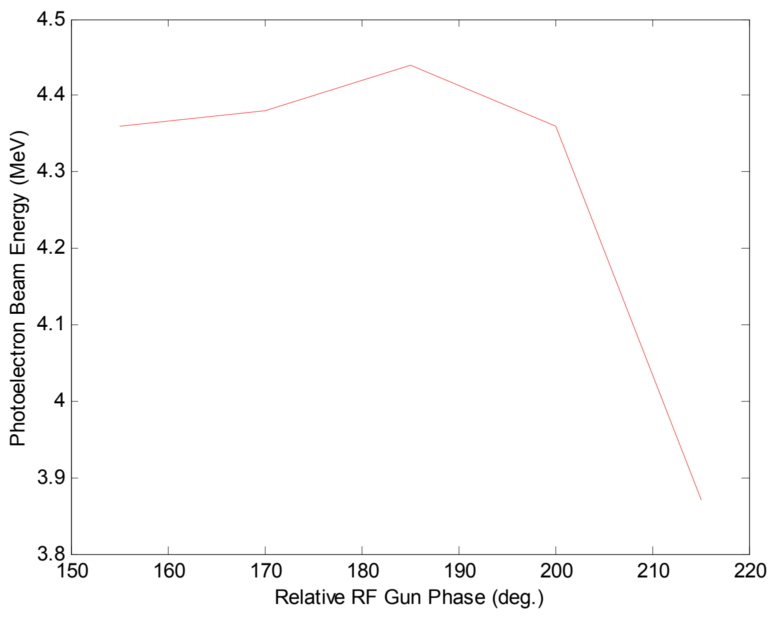
- No timing jitter
- No energy fluctuation
- Perfect point stability
- 7/24 available
- Remote controllable
- NO laser physicist.

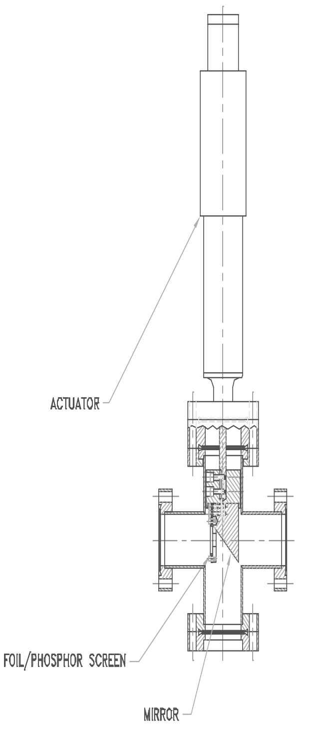
Programmable in both transverse and longitudinal distribution

	rms	peak
Timing jitter	50 - 100, fs	200 - 400, fs
energy	1,%	5,%
Point stability	0.25,	1,%
Transverse uniformity	2.5,%	10,%

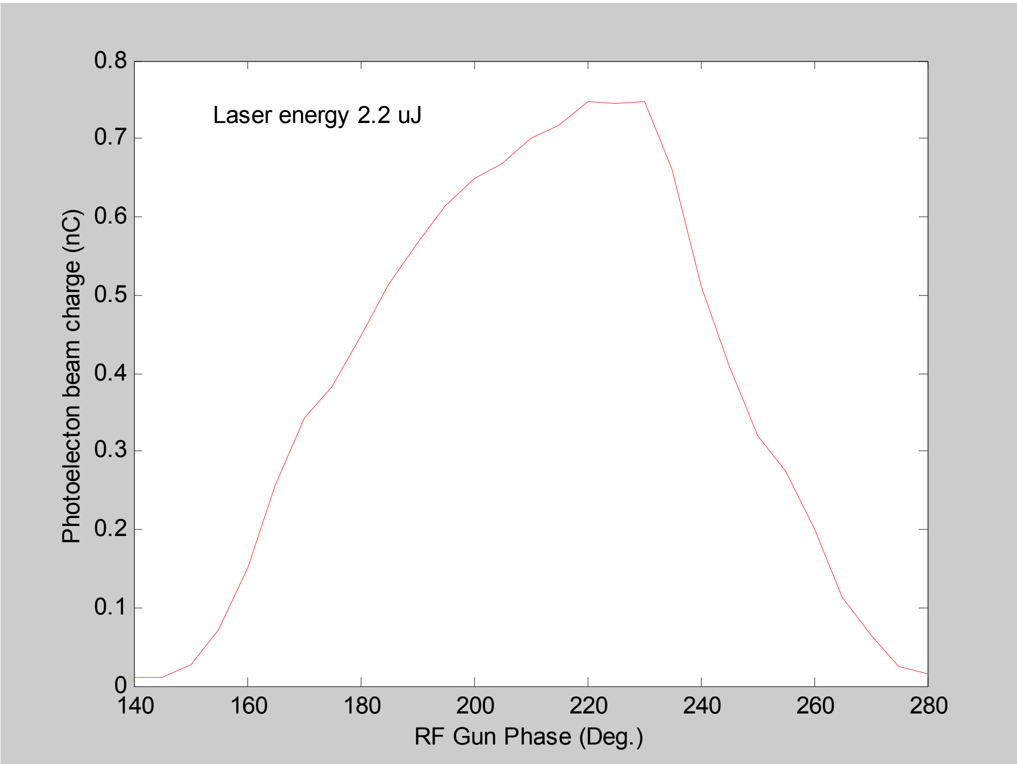
Photo-injector Beam Diagnostics

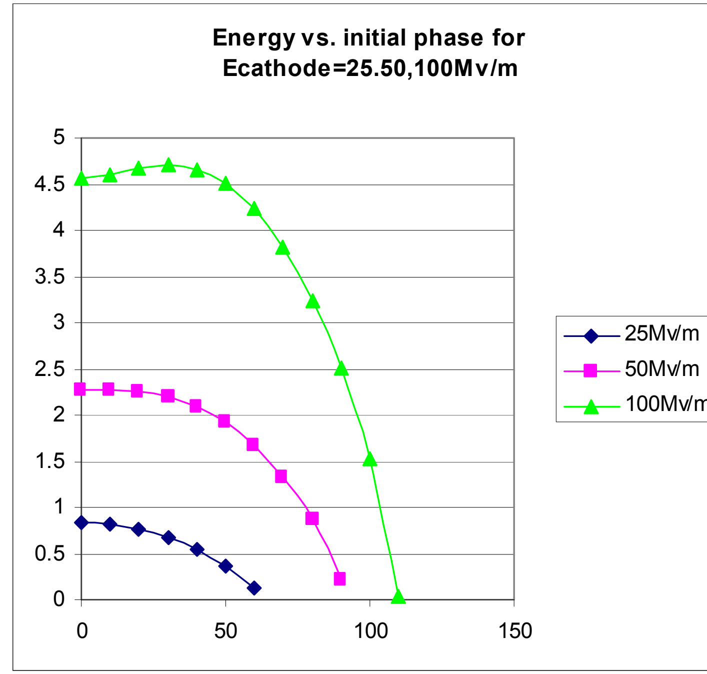
- Energy
- Charge
- RF Gun Phase





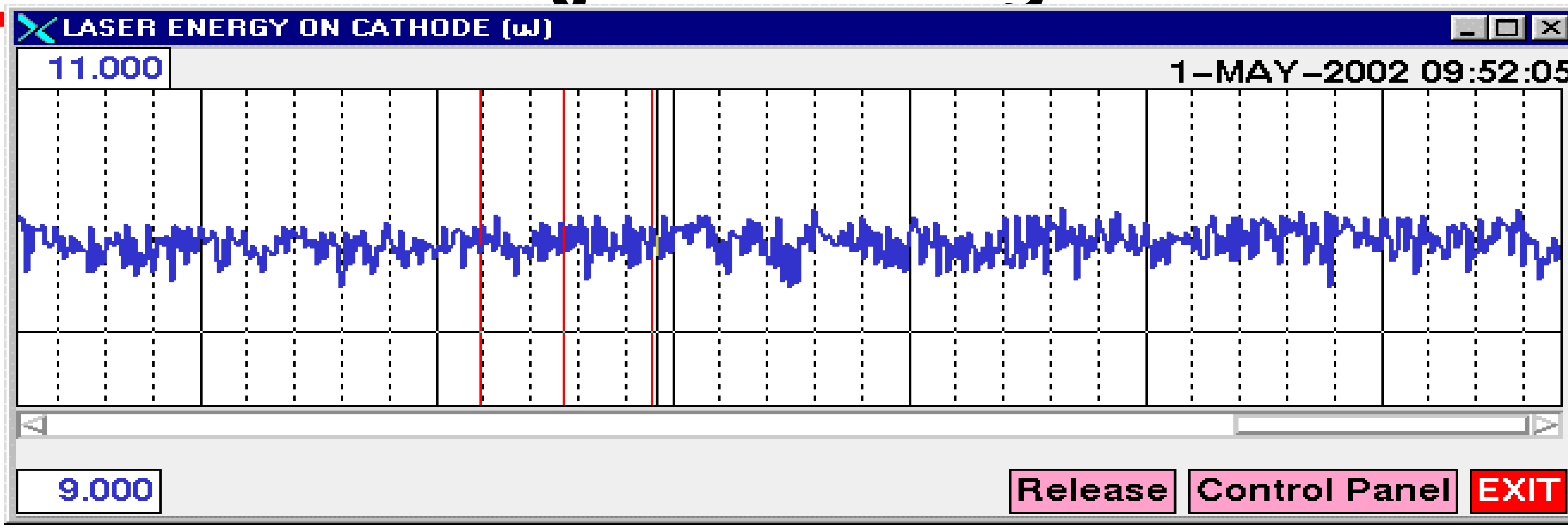
Laser and Photoinjector Characterization

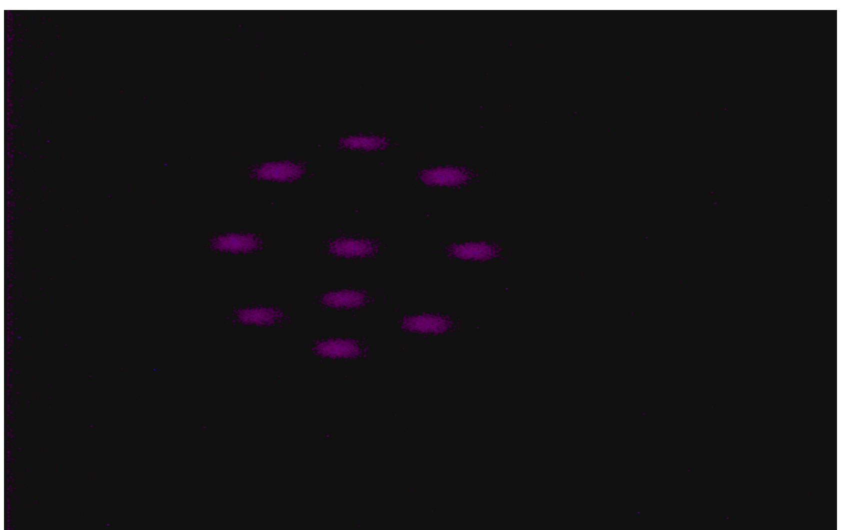


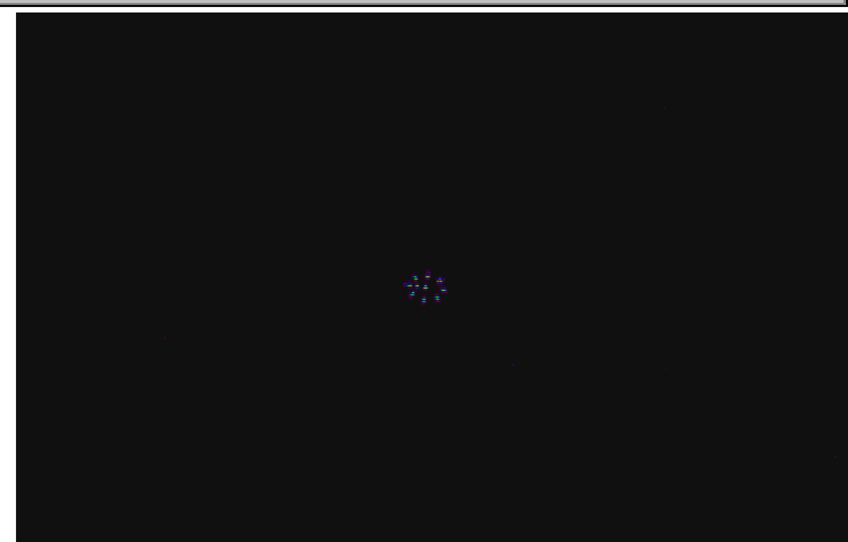


$$Q(\phi) = \int_{-\infty}^{\infty} d\tau A I(\tau)(h\nu - \varphi + \alpha\sqrt{\beta E(\phi - \tau)})^2$$

Photo-injector Diagnostics







Quantum Efficiency Measurements

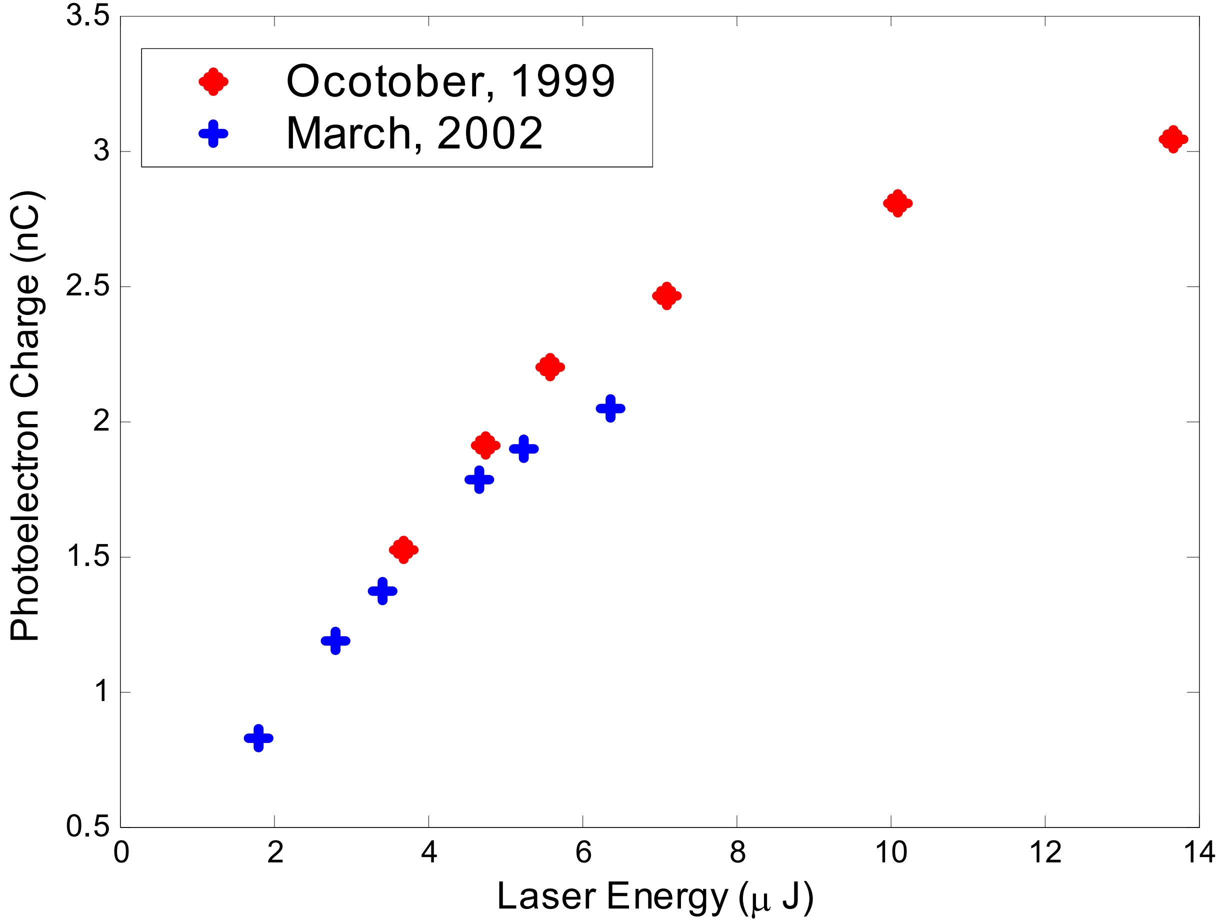
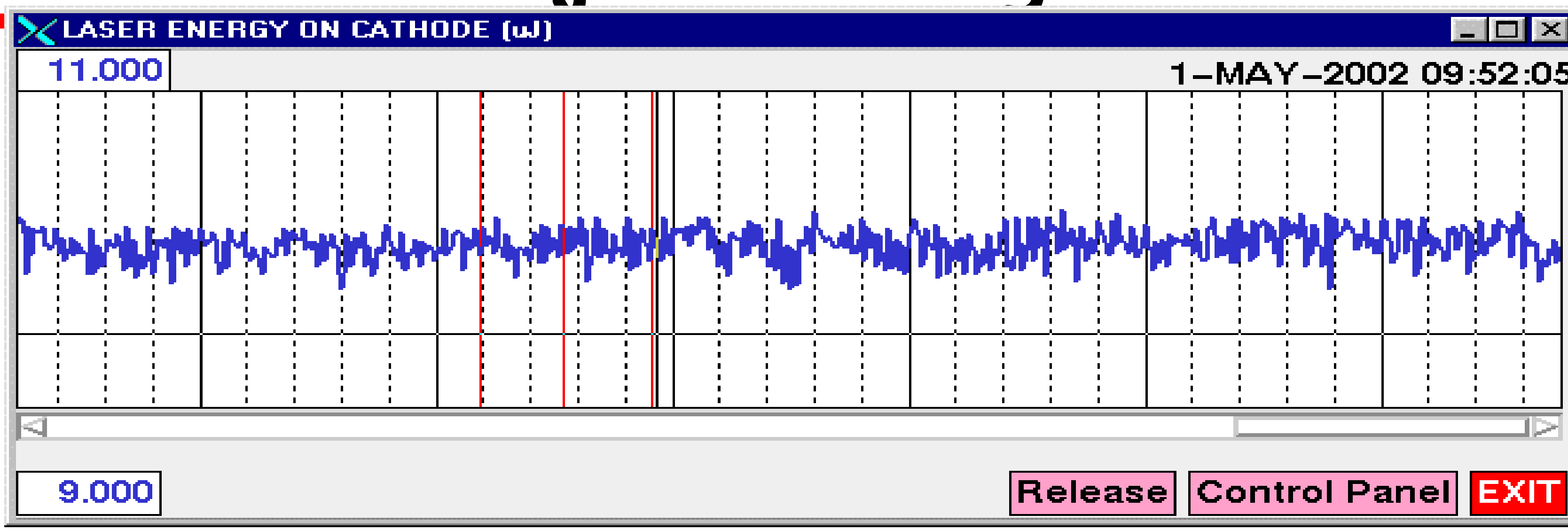
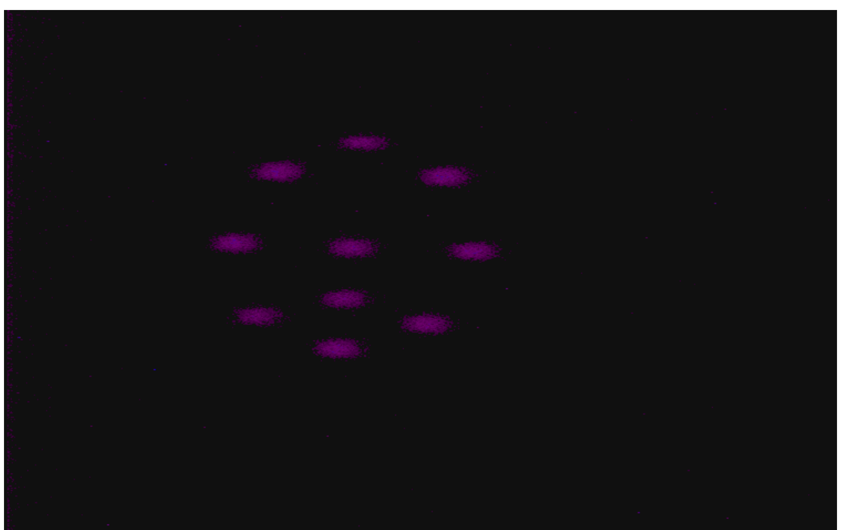
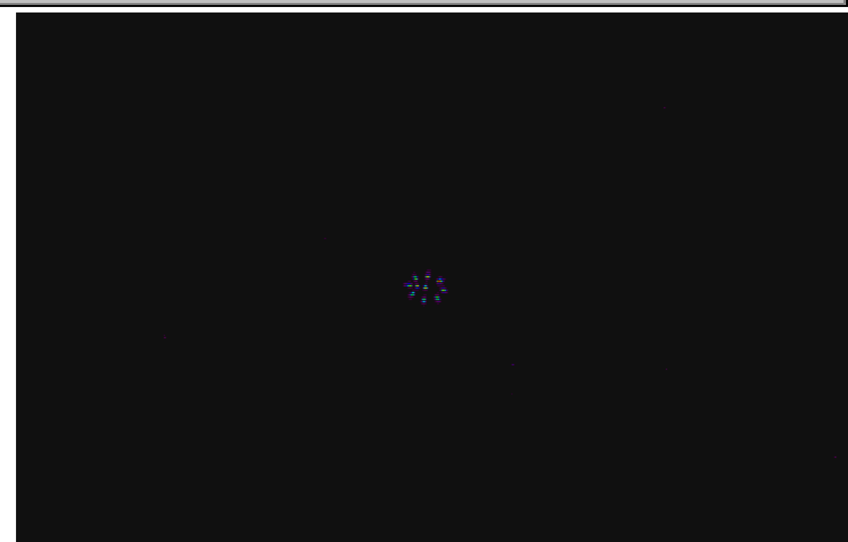
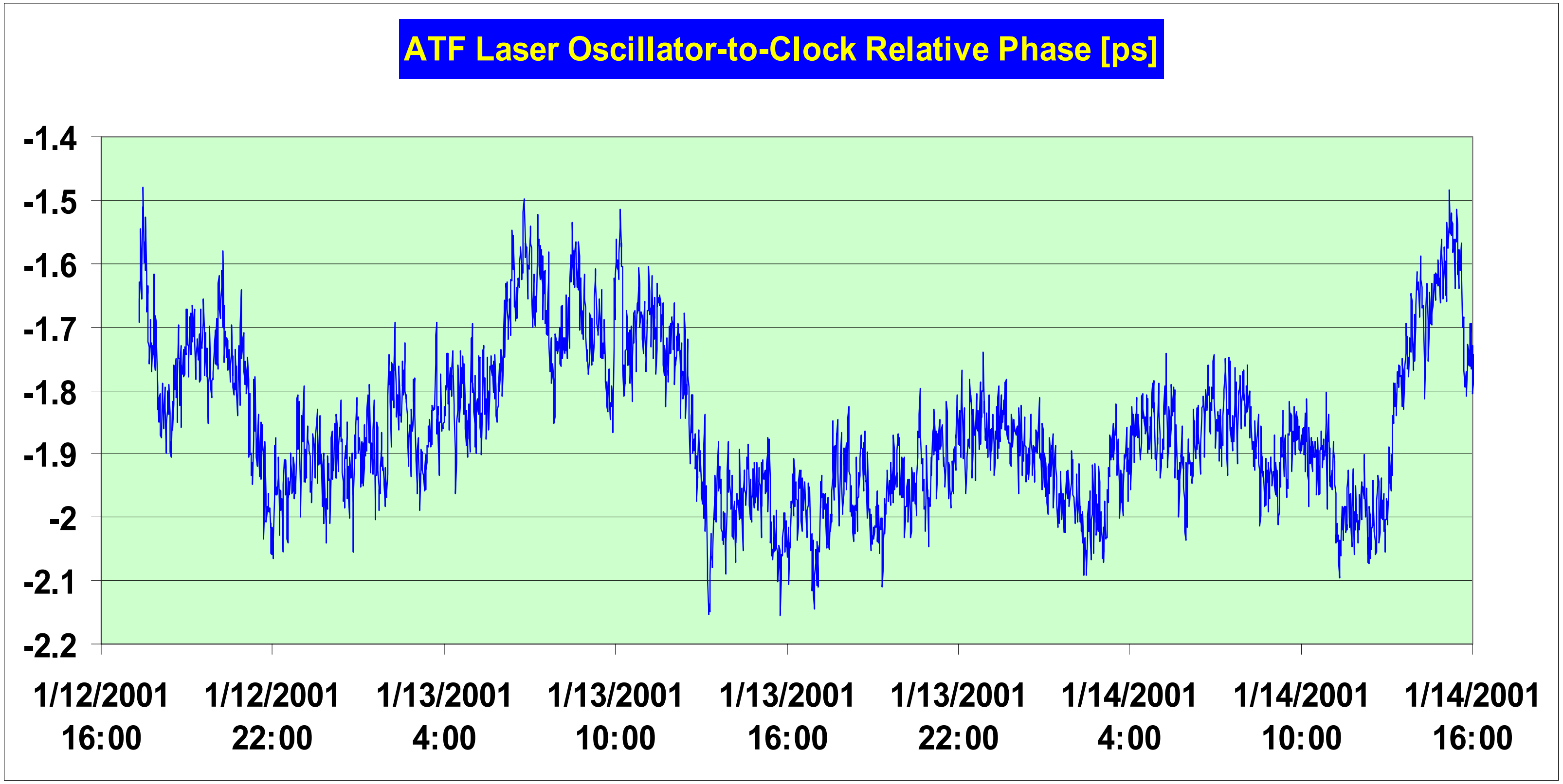


Photo-injector Diagnostics








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
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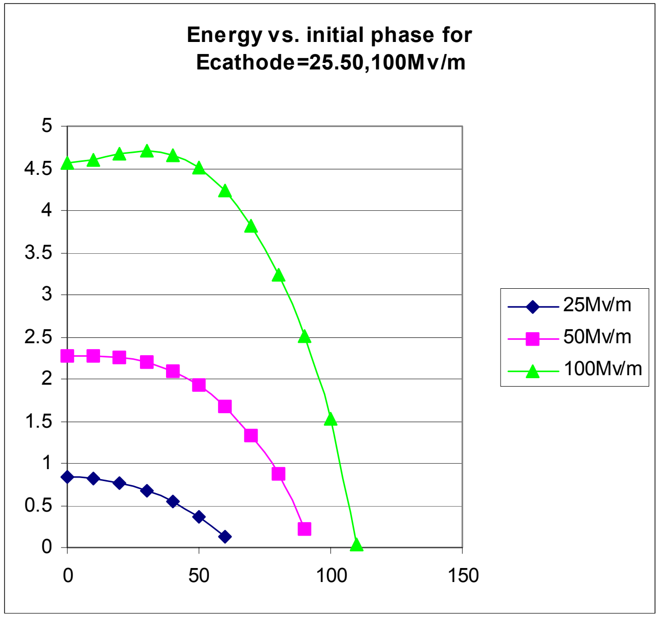
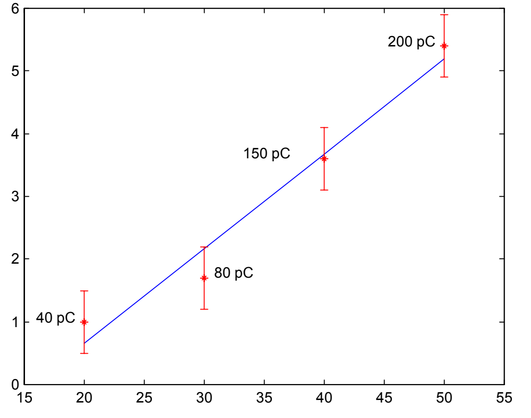
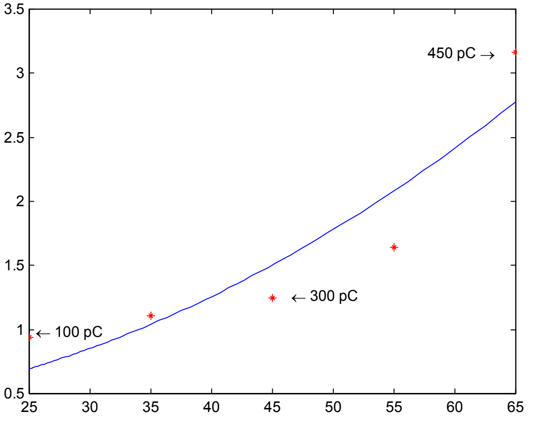
1/14/2001 10:00
1/14/2001 16:00

Longitudinal Emittance Compensation

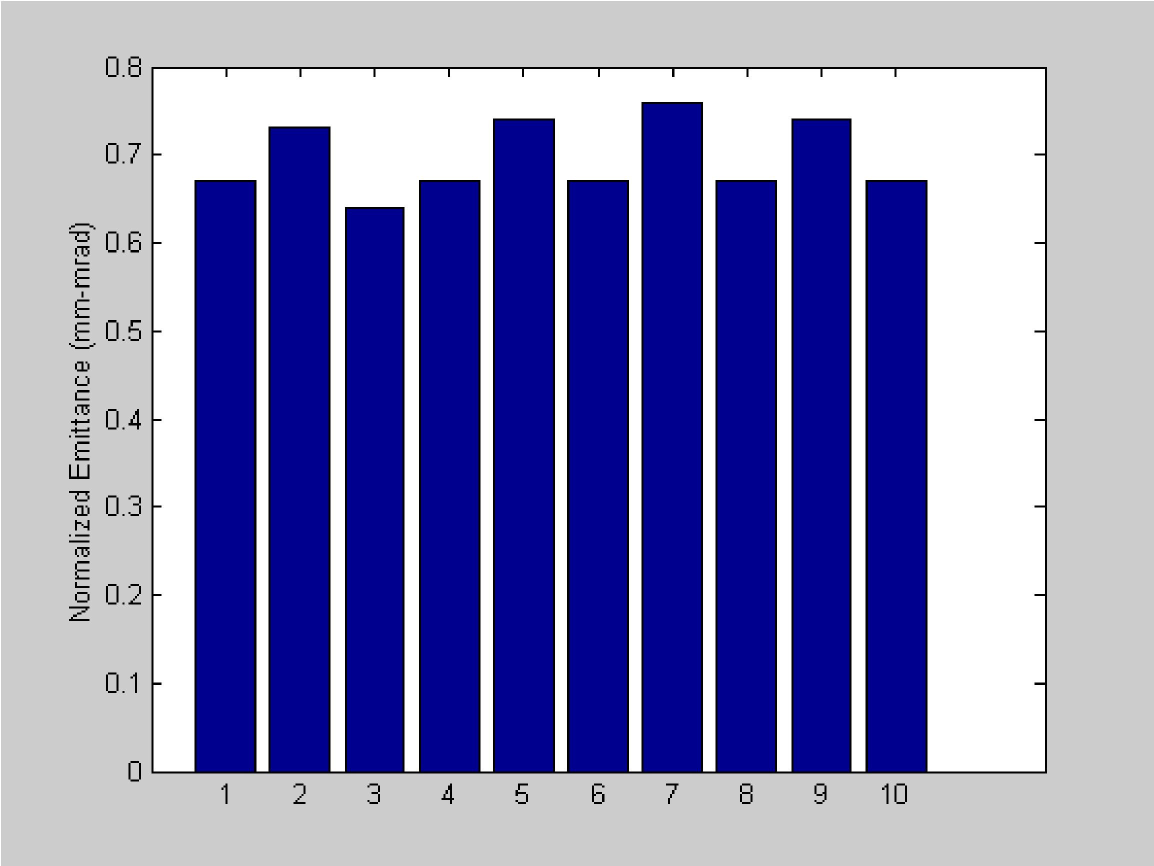




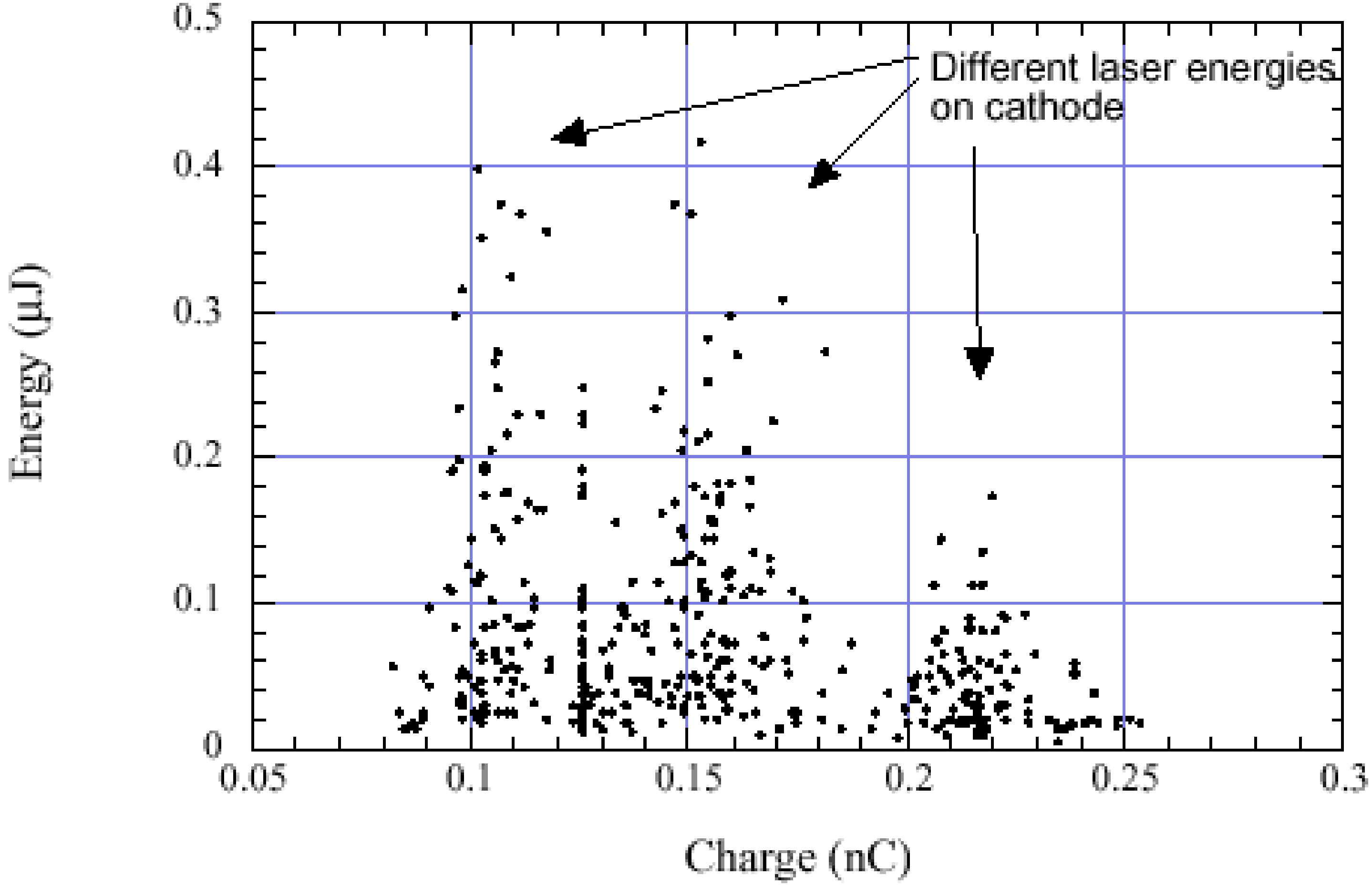


- *Phys. Rev. E. 54, R3121 (1996)*
- *PAC 97*

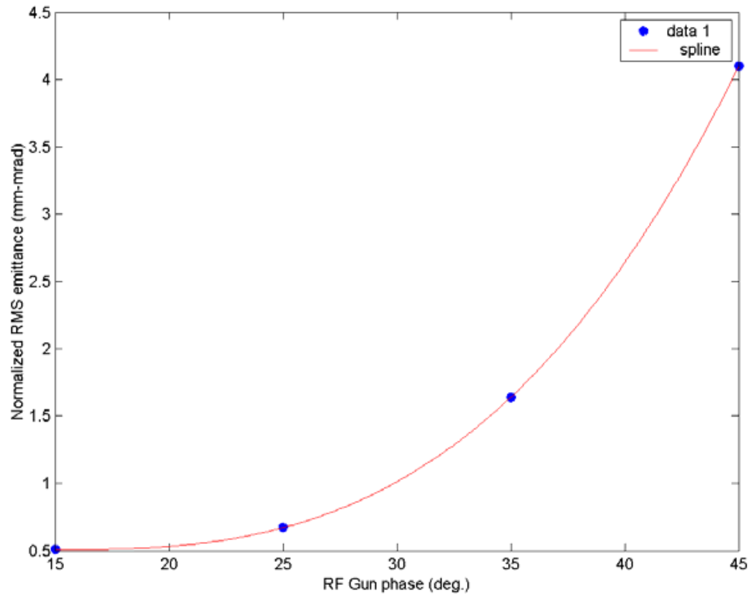
Stability and Reliability Leads To Better Performance

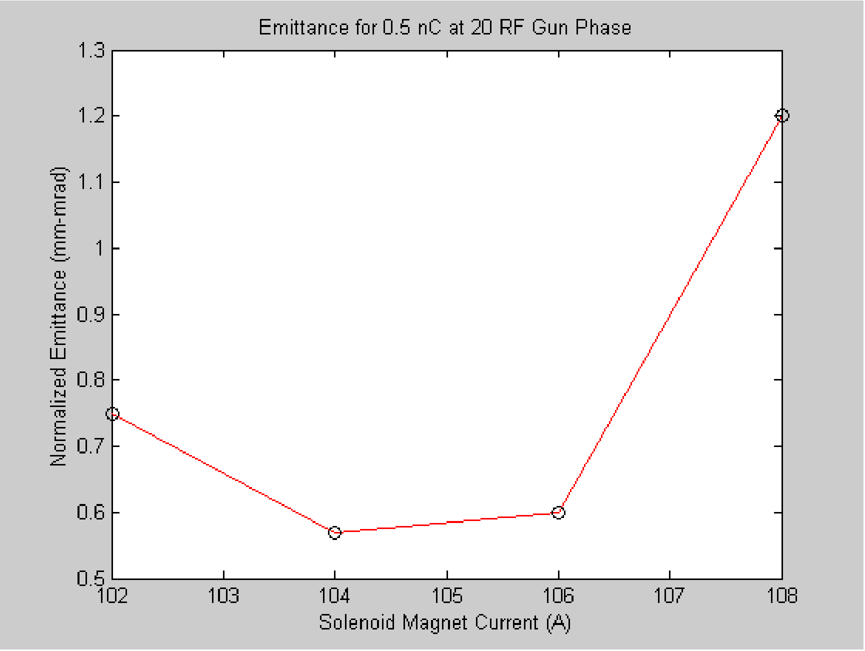


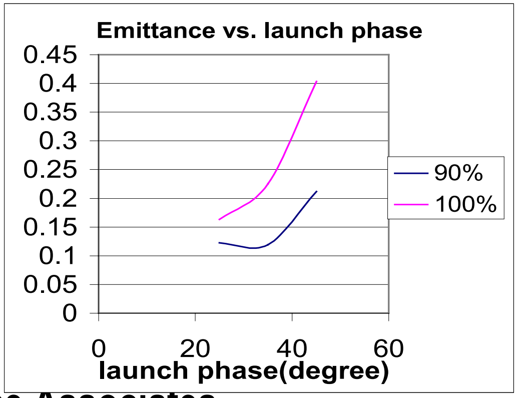
Detector vs. Charge

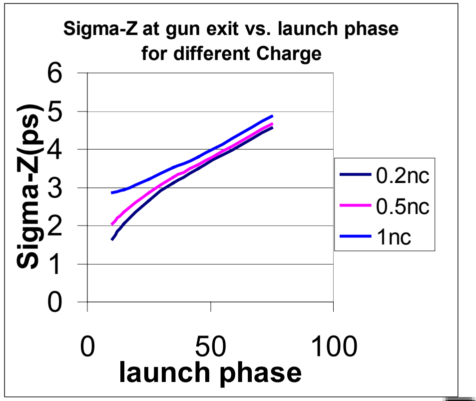


Emittance Optimization at 45 MeV









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Thermal Emittance

Electrons are emitted with a kinetic energy E_k

$$\varepsilon_{th} = \frac{r}{2}\sqrt{\frac{E_k}{m_e c^2}}$$

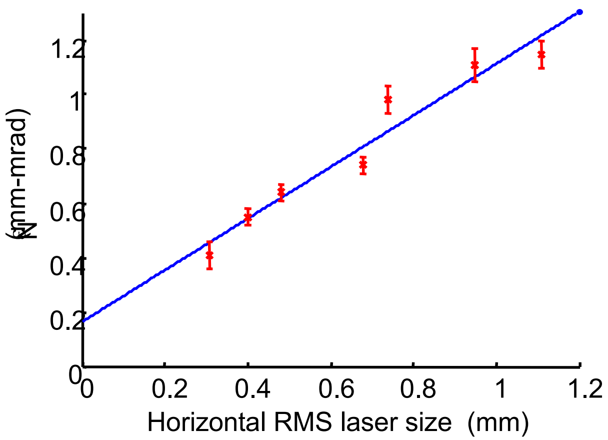
laser spot assumed uniform with radius r

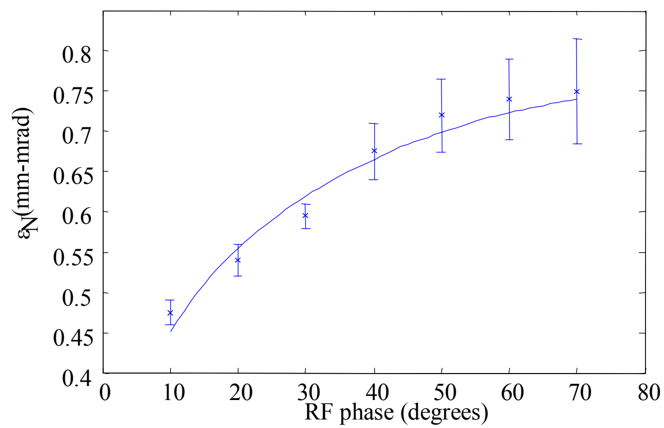
$$E_k = h\nu - \Delta + \alpha\sqrt{\beta_{RF} E_{RF} \sin\theta_{RF}}$$

$$\Delta = \Phi \text{, or } E_G + E_A$$

Example of measurement for Cu-cathode

(Courtesy of W. Graves)

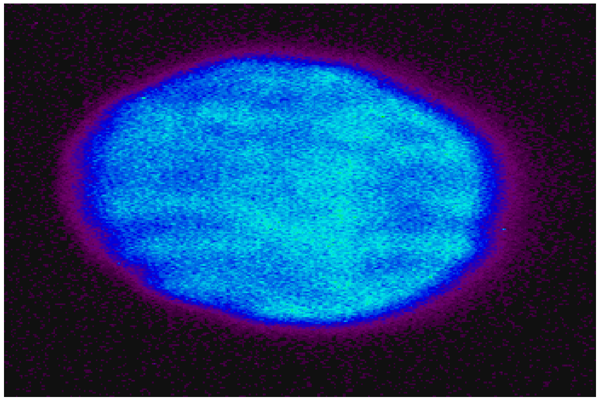




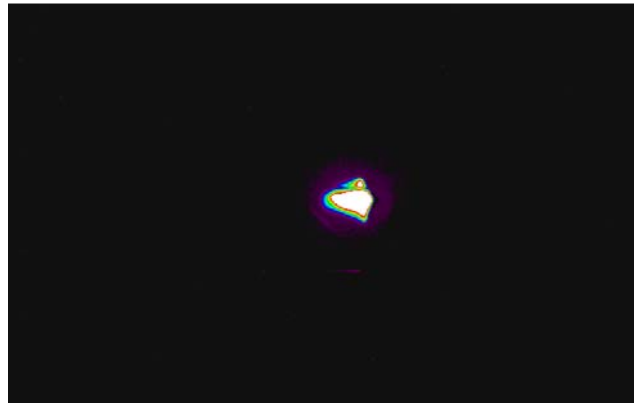
Linear fit gives E_k=0.43 eV

Nonlinear fit gives β_{rf}=3.1+/-0.5, Φ_{cu}=4.73+/-0.04 eV, and E_k=0.40 eV

Performance of Photocathode RF gun Injector



Laser profile on the cathode.



Electron beam at dispersion region.

VERTICAL EMITTANCE

Vertical calculations:

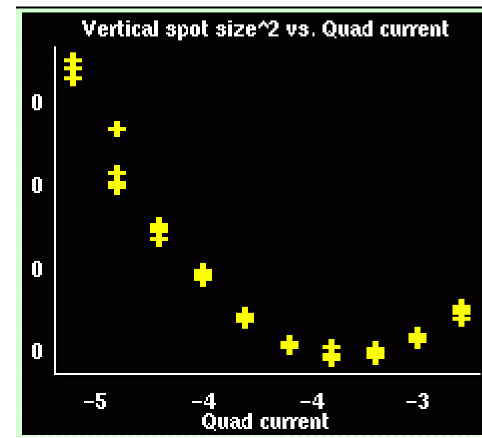
Geometric emittance = 0.019054

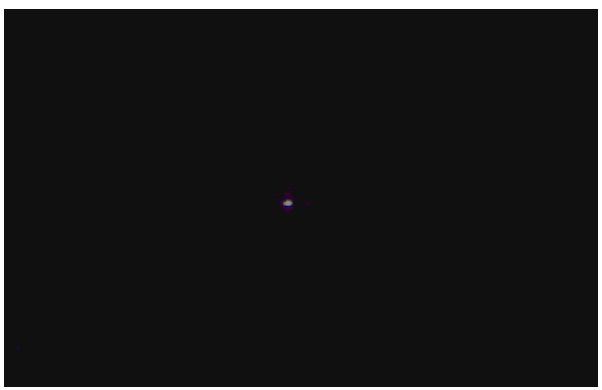
Normalized emittance = 1.121056

Sigma (1,1) = 0.131340

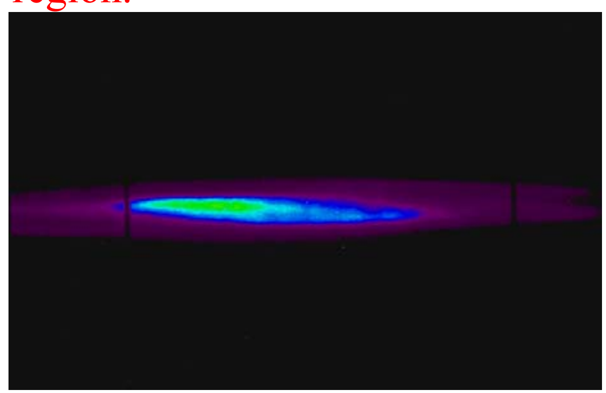
Sigma (1,2) = 0.024247

Sigma (2,2) = 0.007240





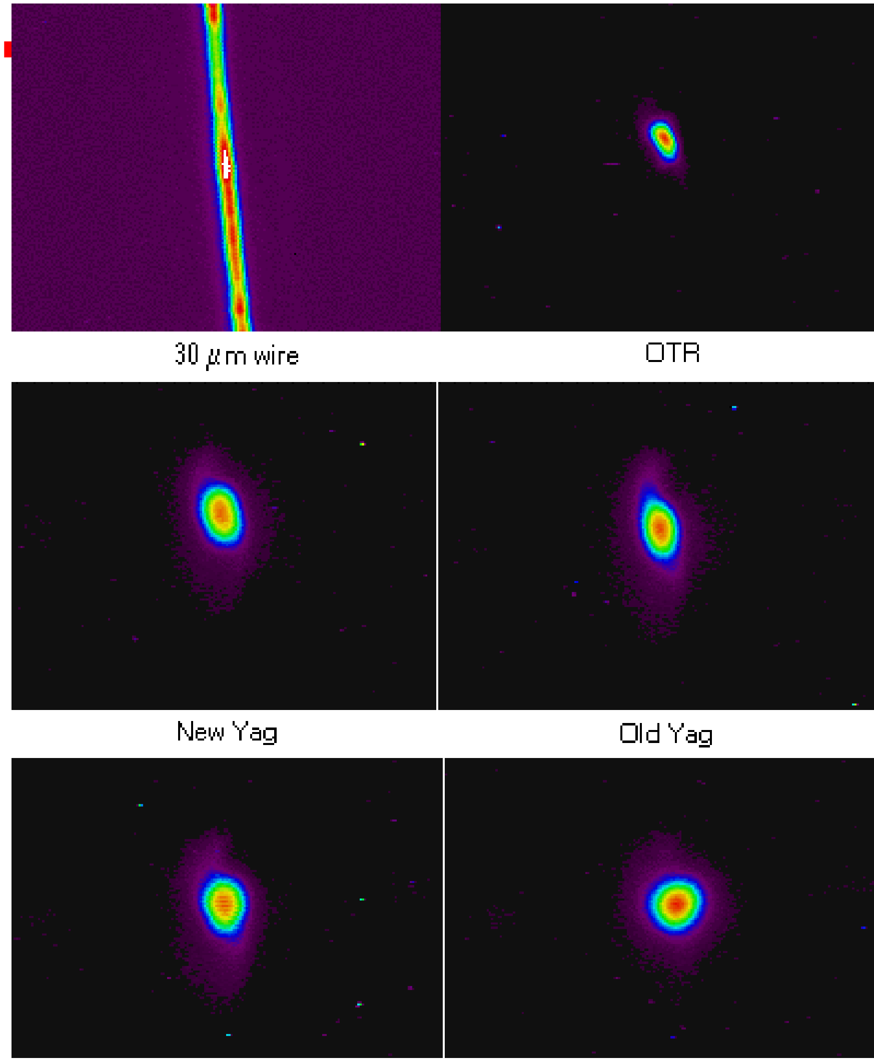
Electron beam focus after the gun.



Electron beam profile on the measurement screen.

Q-scan data for a 30 MeV beam, 200 pC charge with rms normalized emittance 1.1 mm-mrad, bunch length 4 ps FWHM

Small beam size measurements for 0.5 nC charge



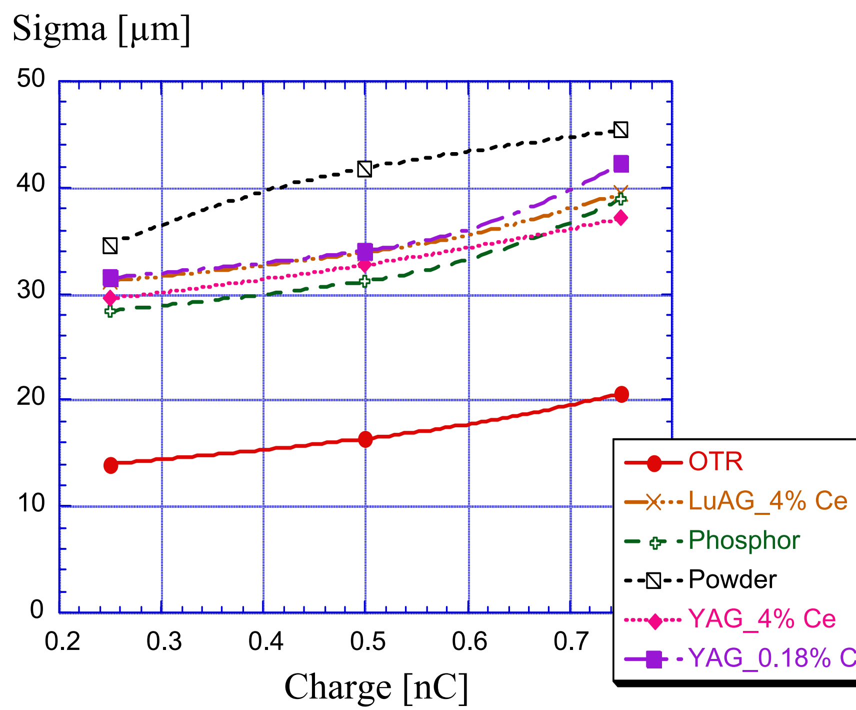
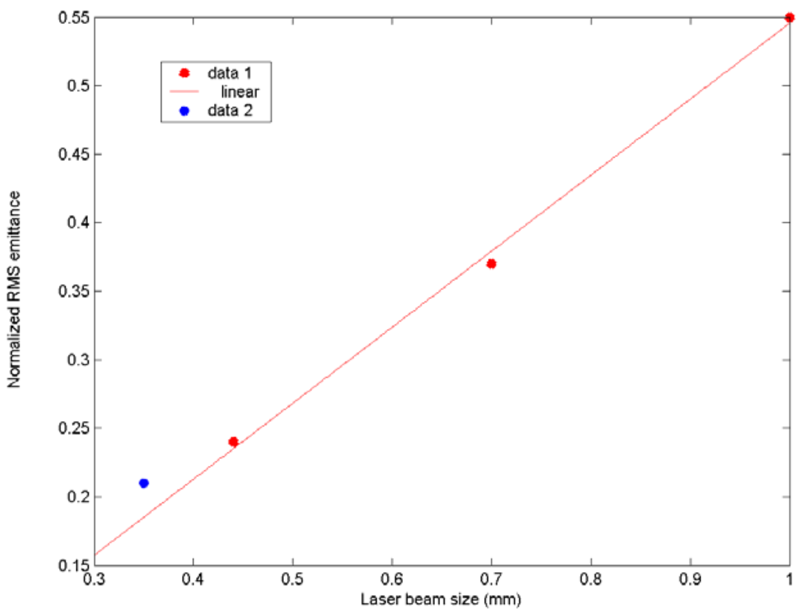


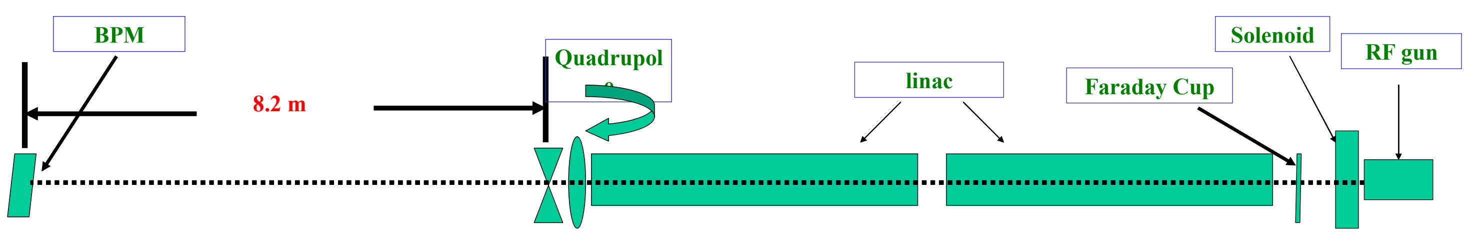
Figure 4: Electron beam horizontal spot size versus charge, measured with the different diagnostics. One can see a big discrepancy between the scintillators and OTR images.

Alex Murdoch et al, PAC 01

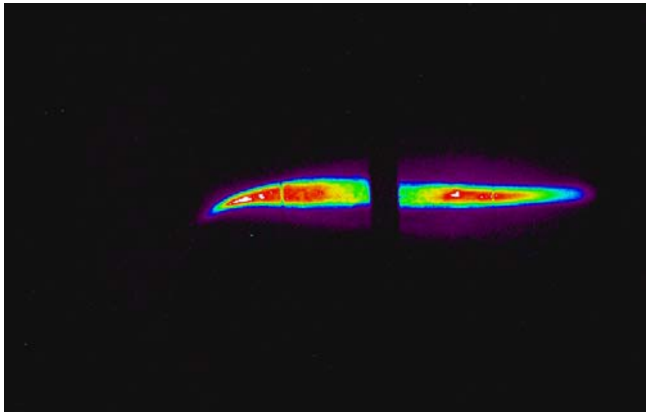
Mg thermal Emittance

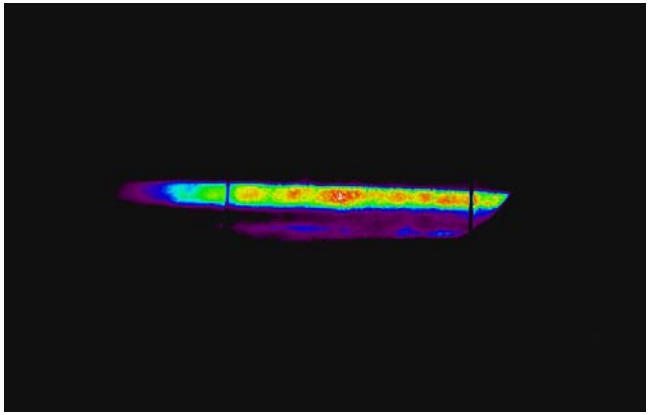


$$\boxed{\Delta\varepsilon_{res} = \frac{\sigma_{res}\sigma_{quad}}{L}, \qquad where\ \sigma_{res}\ is\ a\ const.}$$



Slice Emittance





RF Photoinjector Theory

- Are all emittance uncorrelated?

$$\varepsilon = \sqrt{\varepsilon^2{}_{ther} + \varepsilon^2{}_{rf} + \varepsilon^2{}_{sc}}$$

K-J.'s theory:

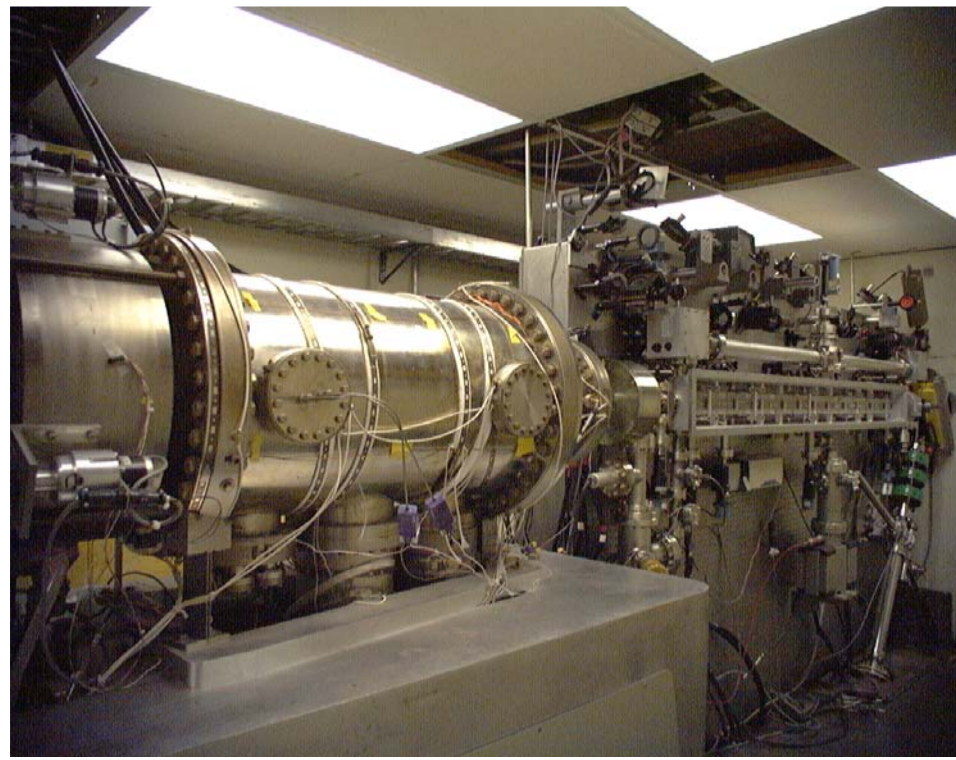
$$\varepsilon_{nx}{}^{sc} = \frac{\pi}{4}\frac{1}{\alpha k}\frac{1}{\sin\phi_0}\frac{I}{I_A}\mu_x(A)$$

Emittnace growth (Rieser):

$$\frac{\varepsilon_{nf}}{\varepsilon_{ni}} = \left[1 + \frac{N r_c \tilde{x}}{15\sqrt{5}\gamma_0 \varepsilon_{ni}{}^2}\frac{U}{w_0}\right]^{1/2}$$

The Advanced FEL Photoinjector Operates at 20 MV/m Gradient and 200 mA Average Current

- 1300 MHz
- E_b = 15-20 MeV
- $\bar{I}_{macro}$ = 100-400 mA
- Q = 1-4 nC
- ε_{rms} = 1.6 mm-mrad
- $\Delta\gamma/\gamma$ = 0.2%
- Injection ϕ = 30^o
- Solenoid = 300A
- Bucking Sol. = 310A



(D. Nguyen's talk at BNL PERL workshop, Jan 2001)

Typical operating parameters

**** determined in the RF gun with a picosecond Nd:YAG laser ****

(1) Laser injection phase in RF gun : 30°

⇒ *for a maximum energy with low emittance*

(2) Linac RF phase : 47°

⇒ *for a minimum energy spread*

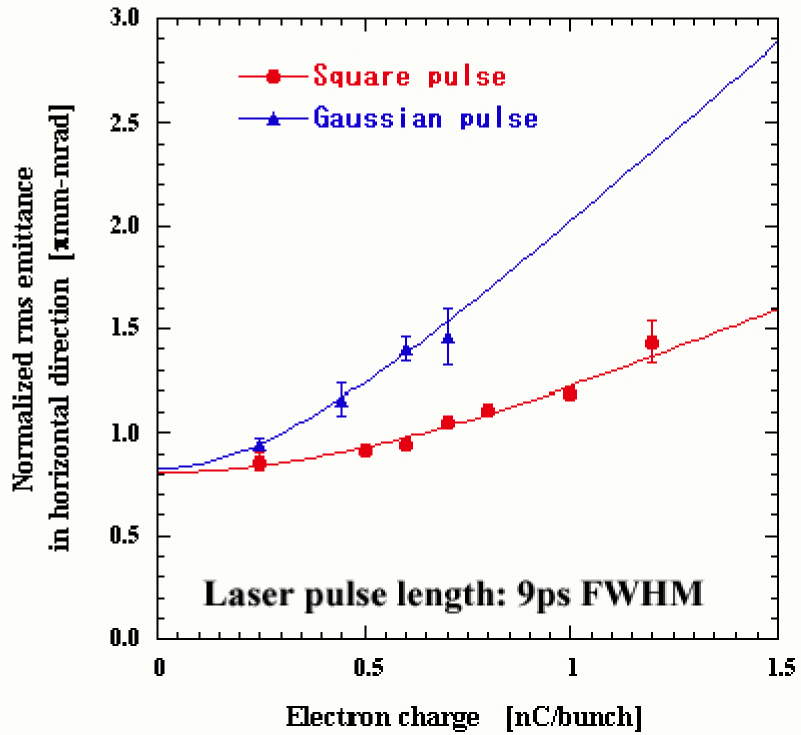
(3) Solenoid magnetic field : 1.57kG

⇒ *For an optimal emittance compensation at 0.6nC, 14MeV*

FESTA

Sumitomo Heavy Industries, Ltd.

Emittance measurements for gaussian and square laser pulse shapes



$$\varepsilon_n = \sqrt{(a' \cdot Q)^2 + b'^2}$$

	a'	$b' = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{th}^2}$
	πmm-mrad/nC	πmm-mrad
Gaussian(9ps) Square (9ps)	1.85±0.13 0.92±0.05	0.83±0.05 0.81±0.03

The reduction of the linear space-charge emittance for the square pulse shape:
~50%.

FESTA

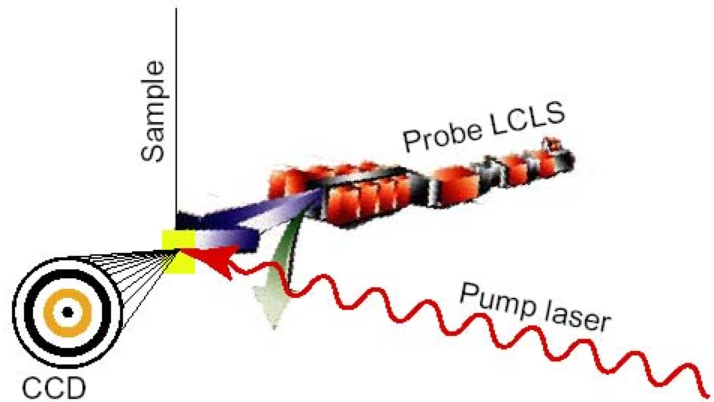
Sumitomo Heavy Industries, Ltd.

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

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

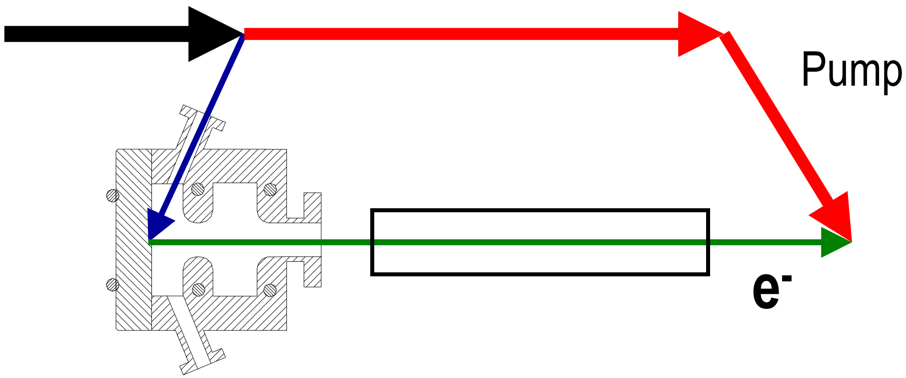
$$\tau_{jitter} \prec \tau_{pump} \ or \ \tau_{FEL}$$

$$\tau \le 100\, fs$$

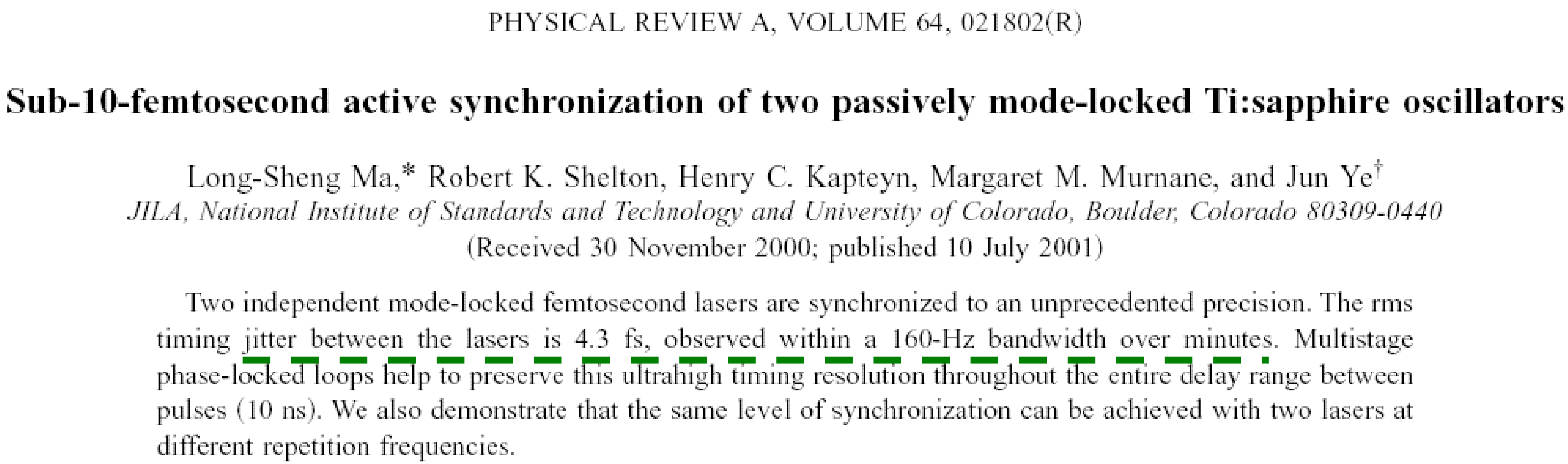


The femtochemistry experiments use an ultrafast laser to initiate the process and the *LCLS* beam as a probe

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



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

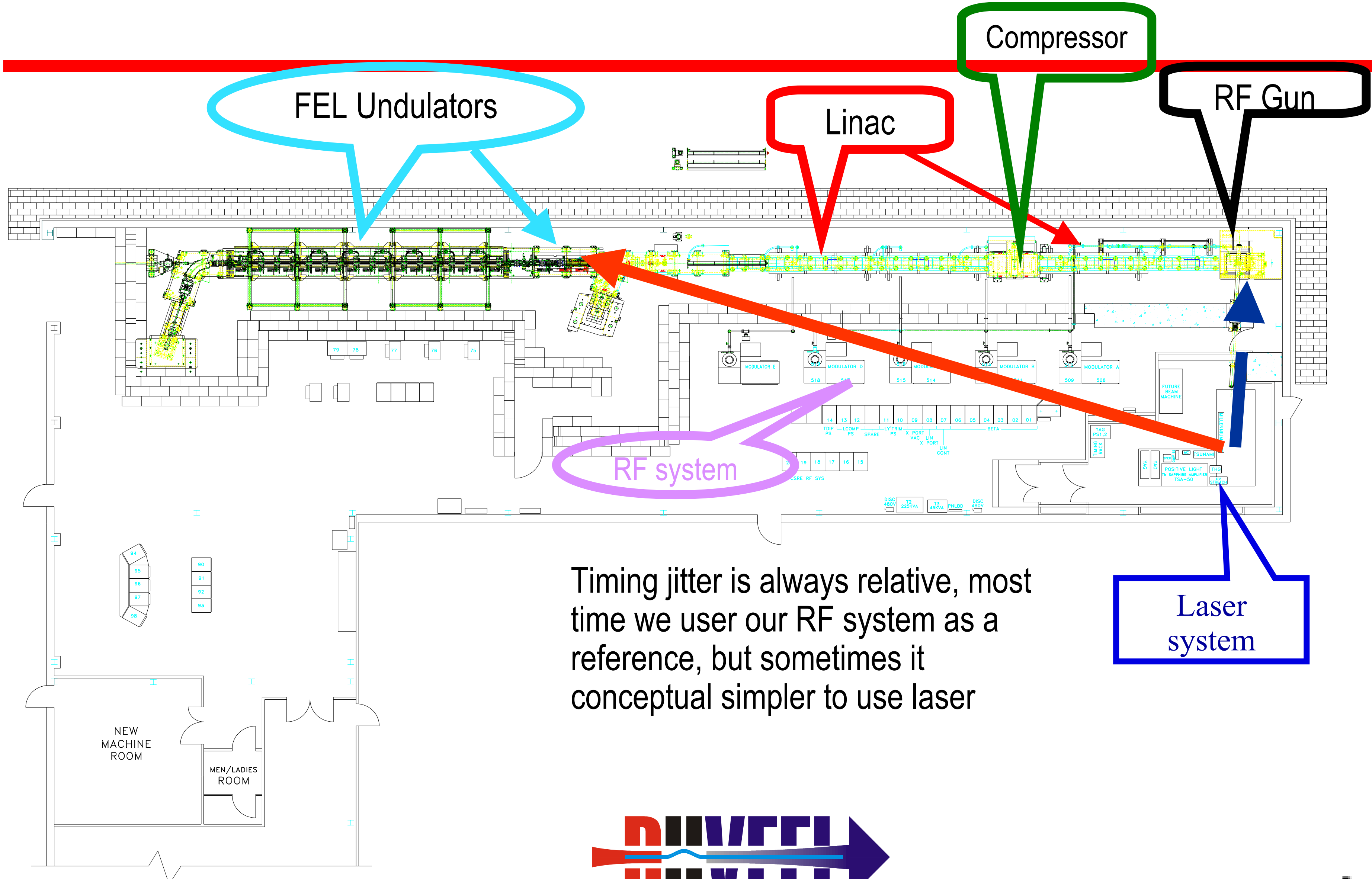

PHYSICAL REVIEW A, VOLUME 64, 021802(R)

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.

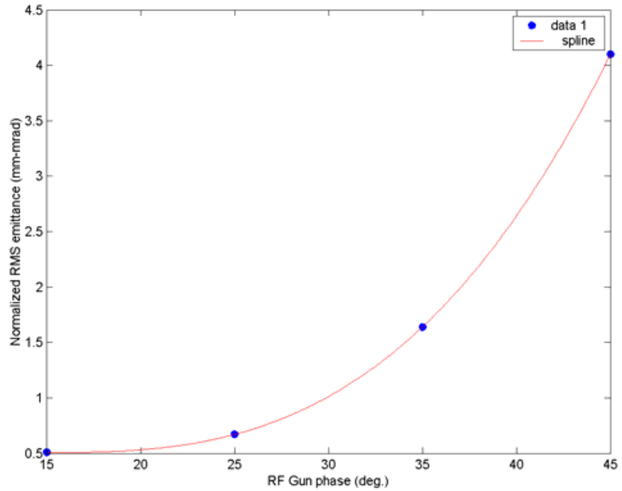
A Typical Photoinjector Based Linac System – BNL DUV-FEL

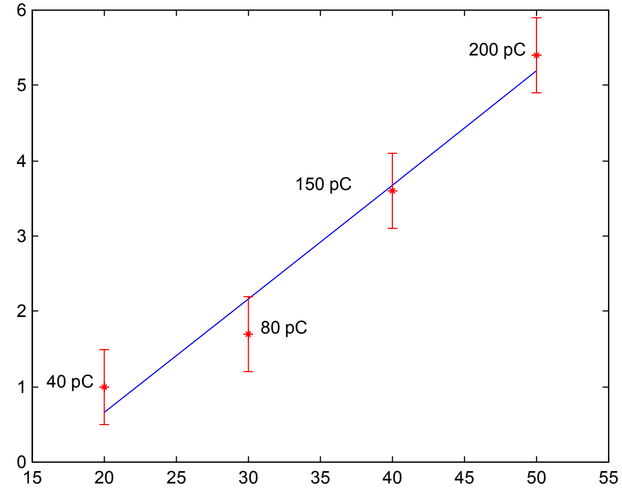


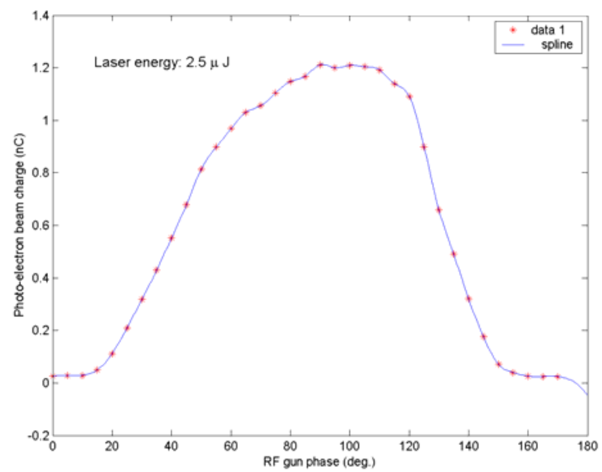
Timing jitter is always relative, most time we user our RF system as a reference, but sometimes it conceptual simpler to use laser

Source Development Laboratory

Timing jitter effects – photocathode RF gun

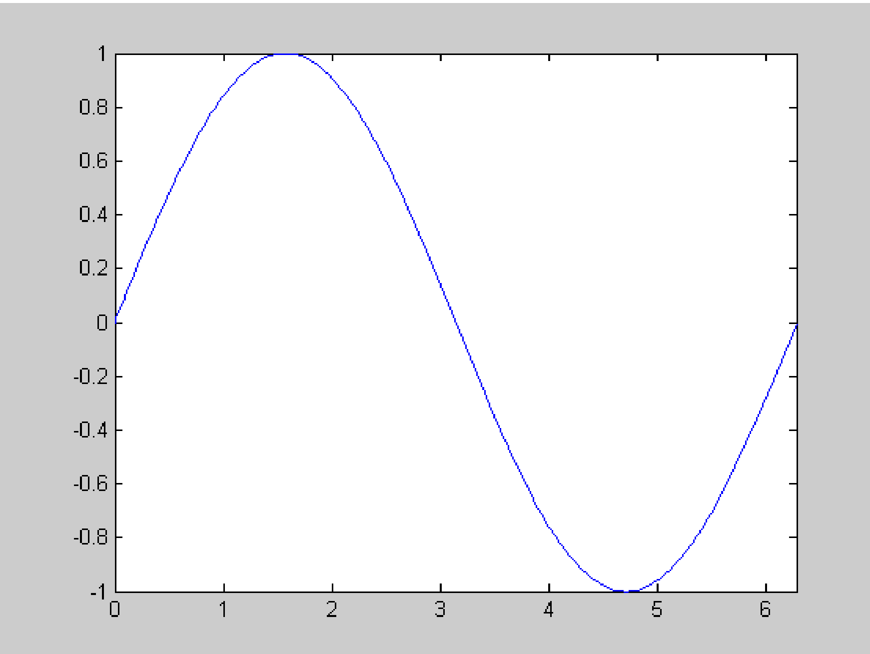


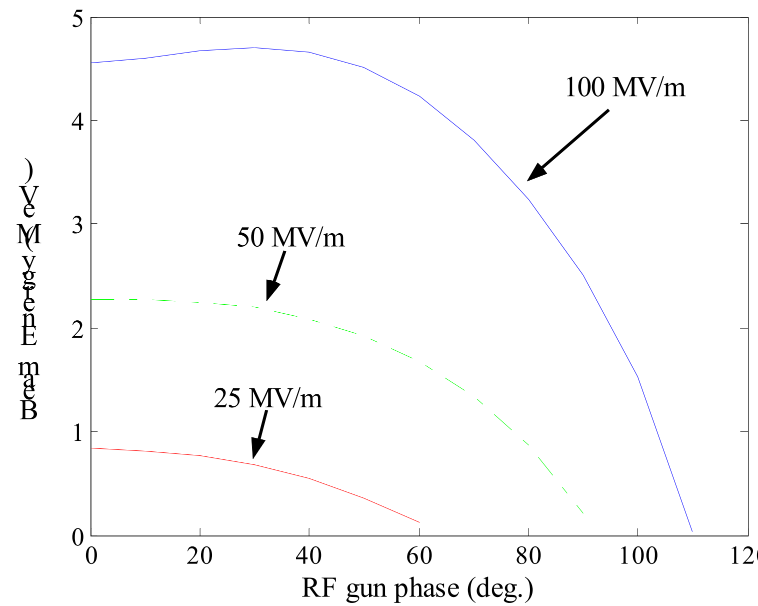




Jitter smaller < 200 fs (rms)

Timing Jitter Due to Energy Fluctuation



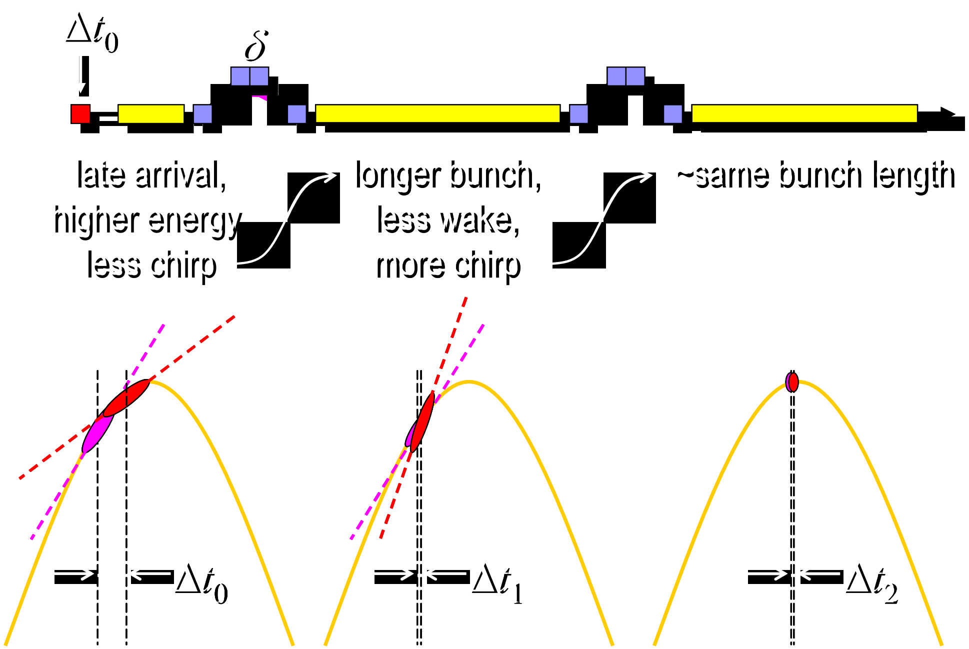


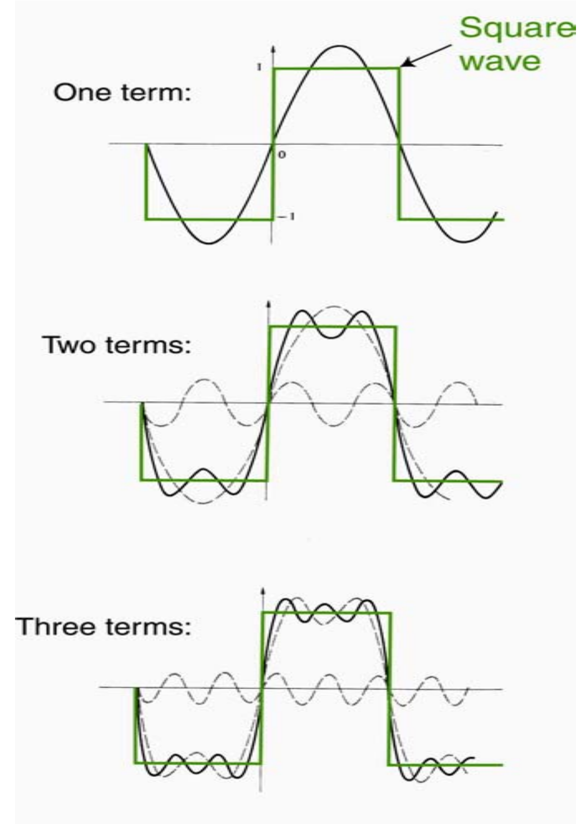
$$\delta t = \int \frac{E(z)}{\gamma^2(z)} \frac{d\ell}{\beta c}, \quad where\ E(z) = \frac{\delta\gamma}{\gamma}\ relative\ energy\ jitter$$

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

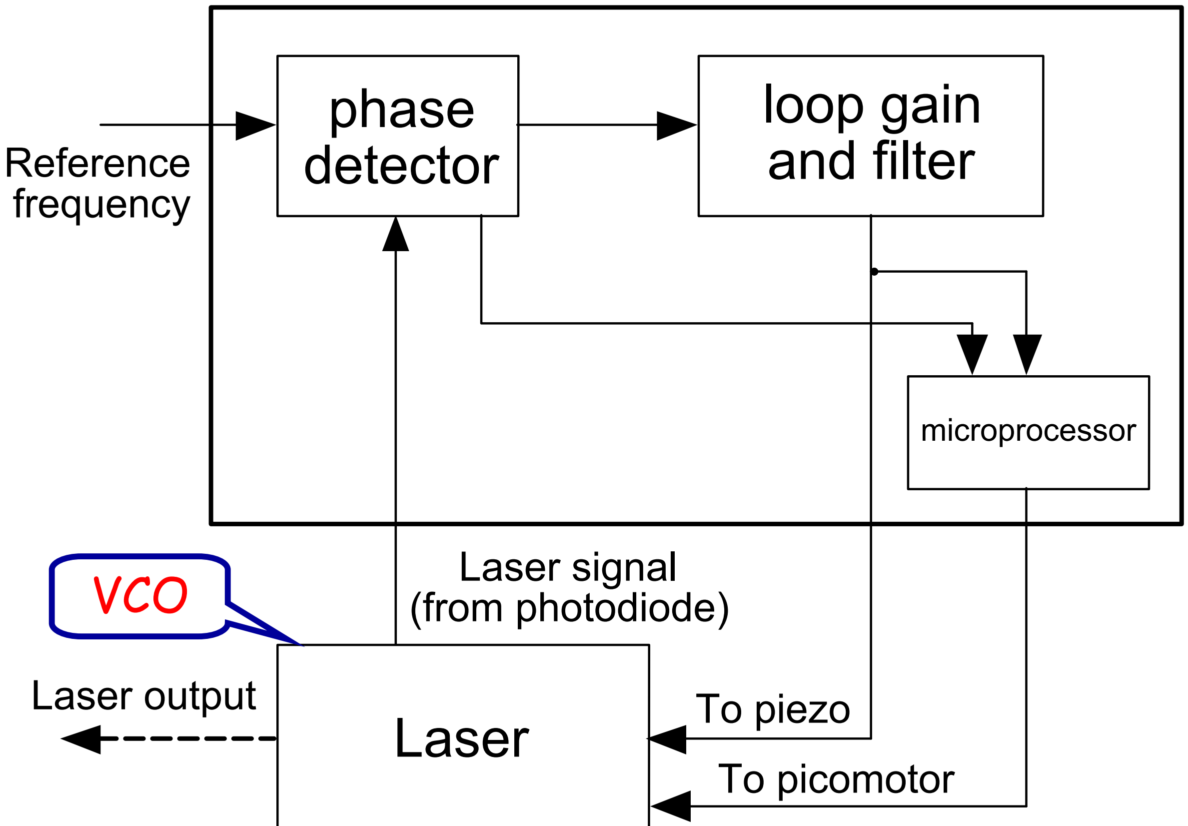
T. Raubenheimer

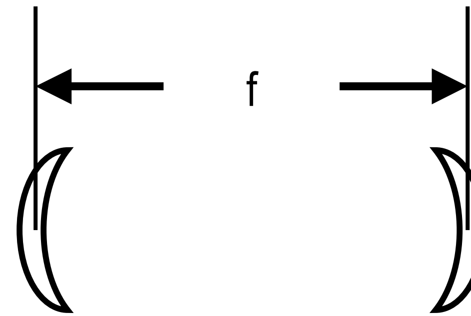
bunch length stability with RF phase jitter…

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

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

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]

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

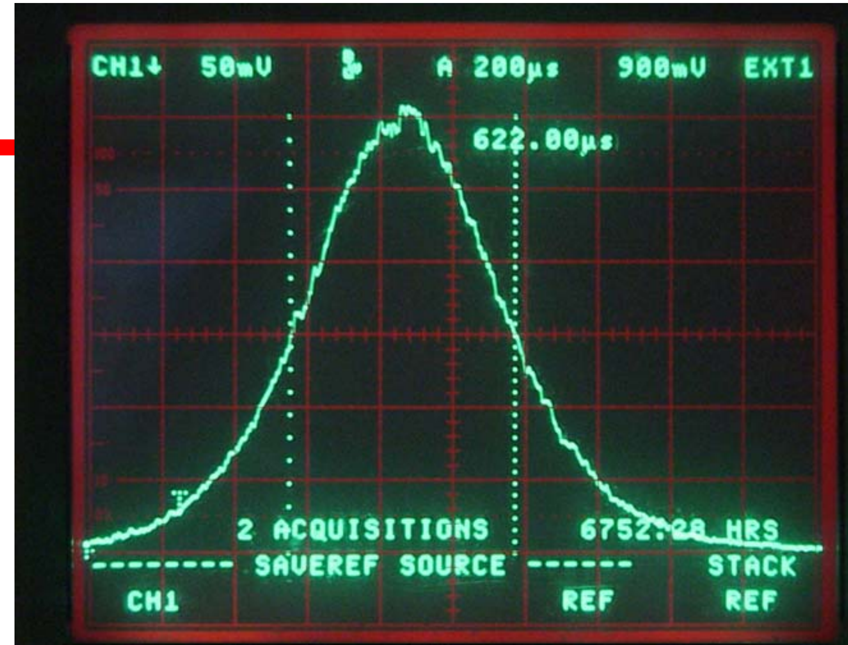
Abstract

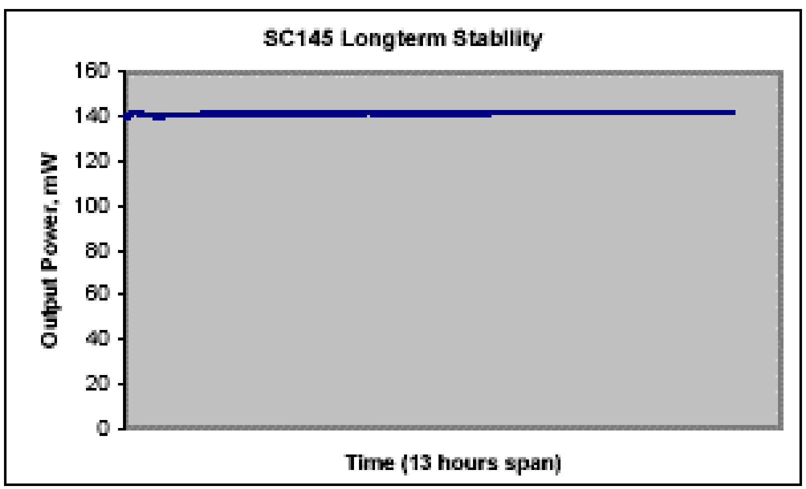
We characterized the phase and amplitude noise of a mirror-dispersion-controlled 10-fs Ti:sapphire laser pumped by a frequency-doubled cw diode-pumped $Nd:YVO_4$ laser and compared with these of the Ti:sapphire laser pumped by an Ar-ion laser. The rms timing jitters and rms amplitude noise for the all-solid-state 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.

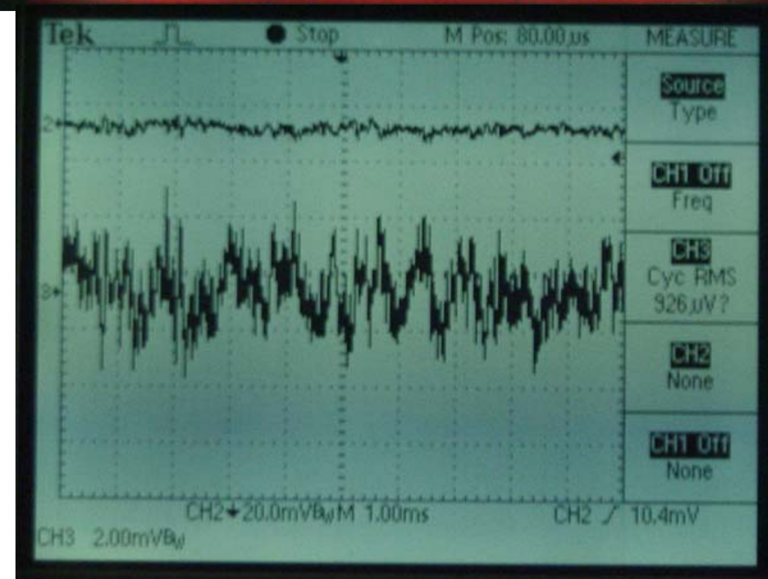
200 fs Yb:glass oscillator

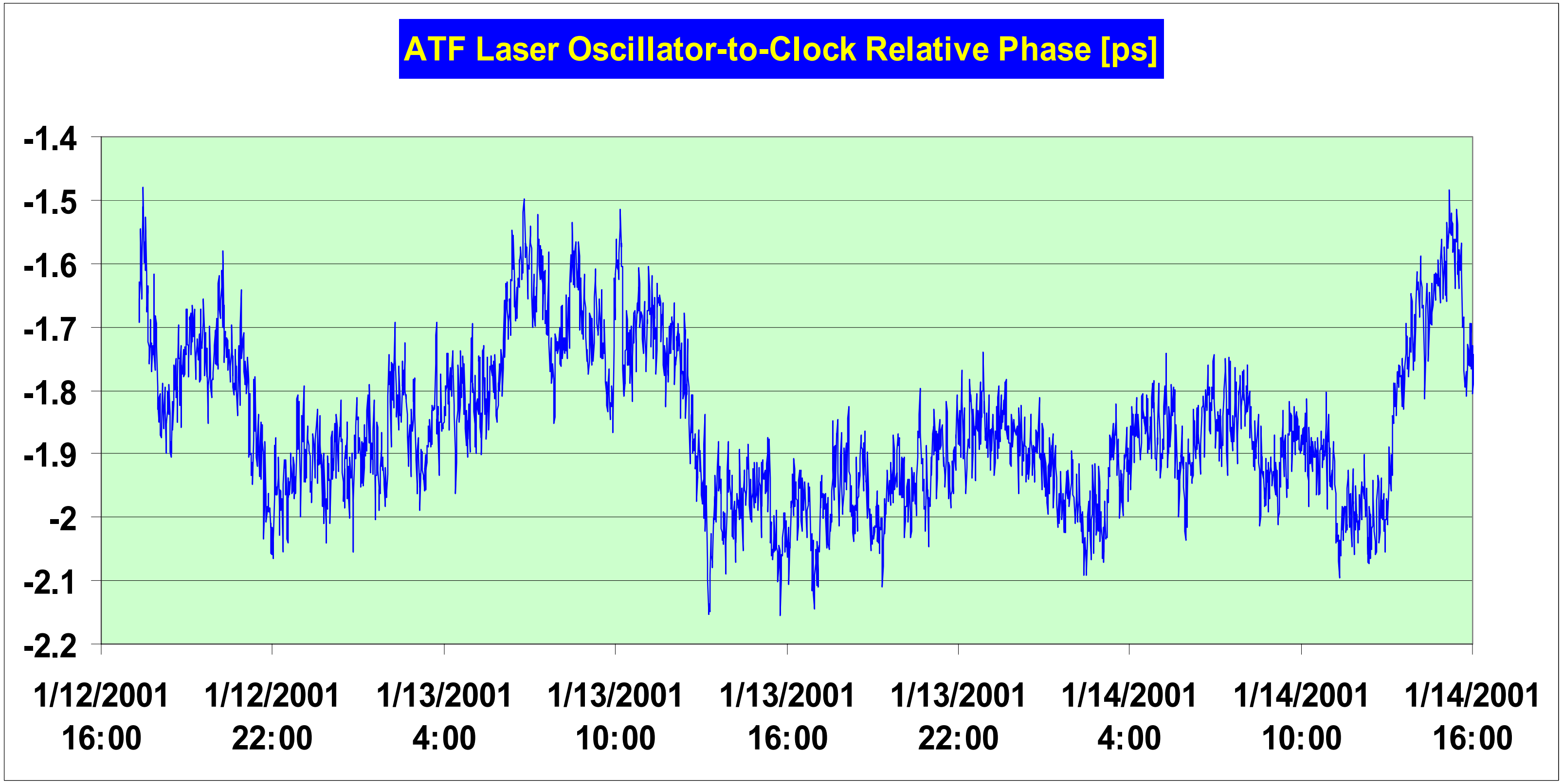
λ(um)	P (mW)	L(FWHM, fs)
1.051	136	150
1.047	117	177

Timing jitter: 200fs (FW, detector limited)

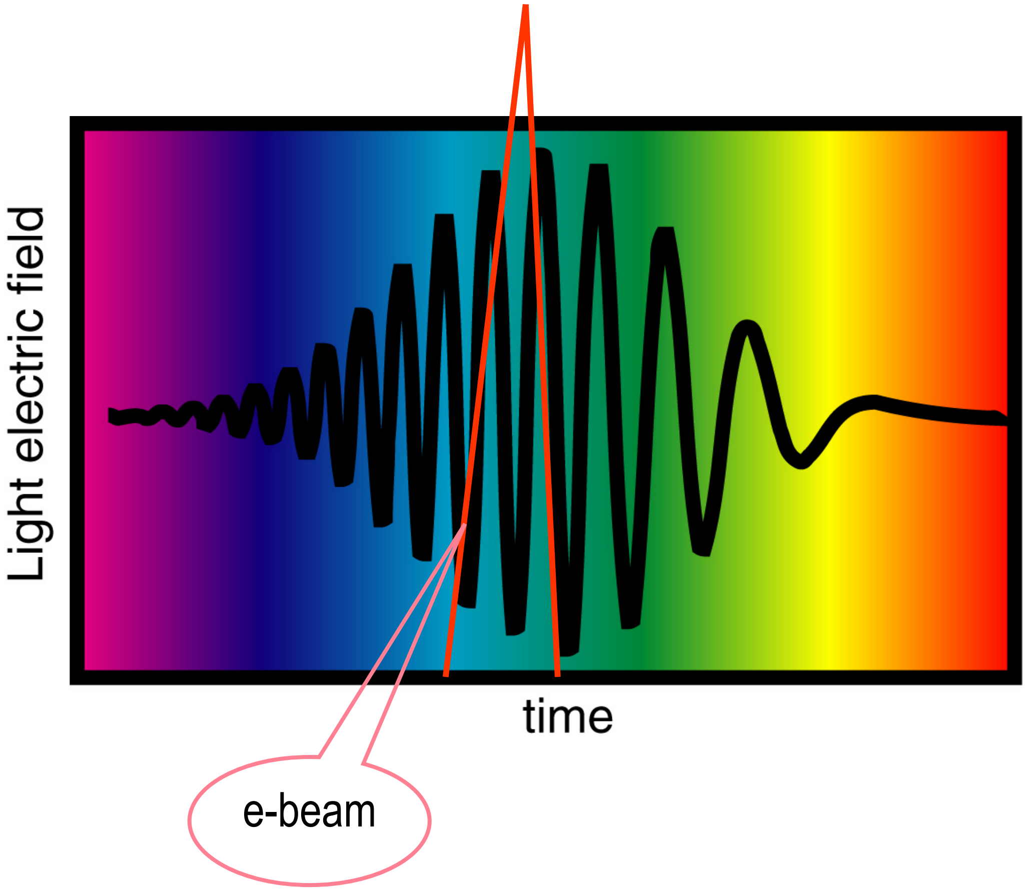


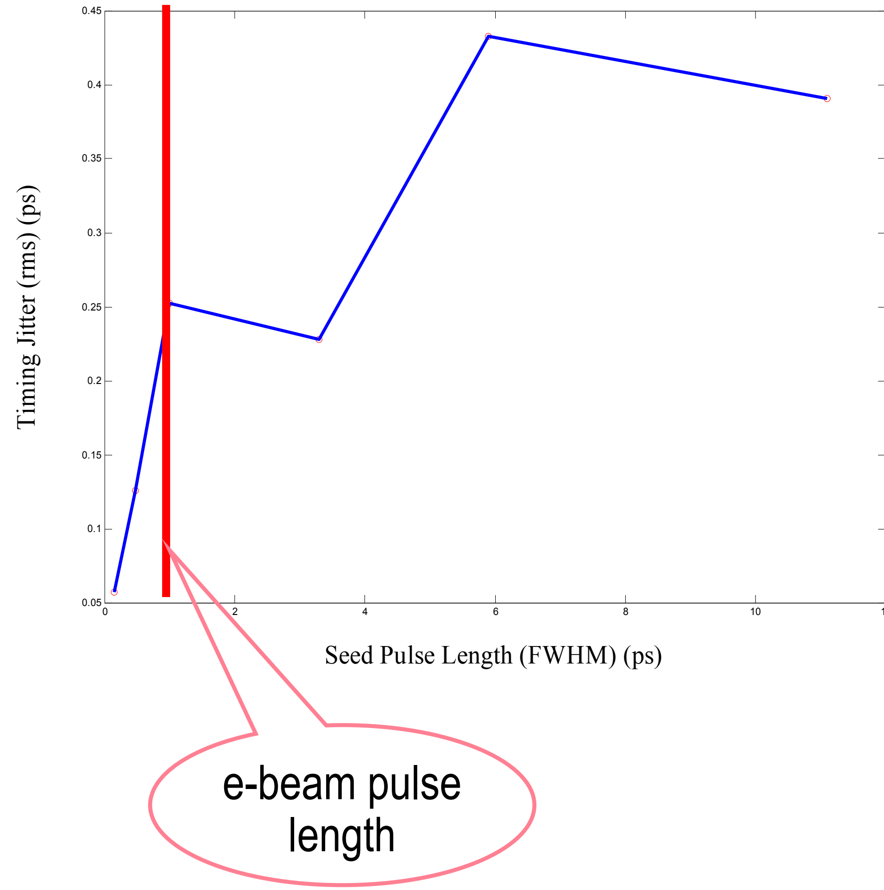


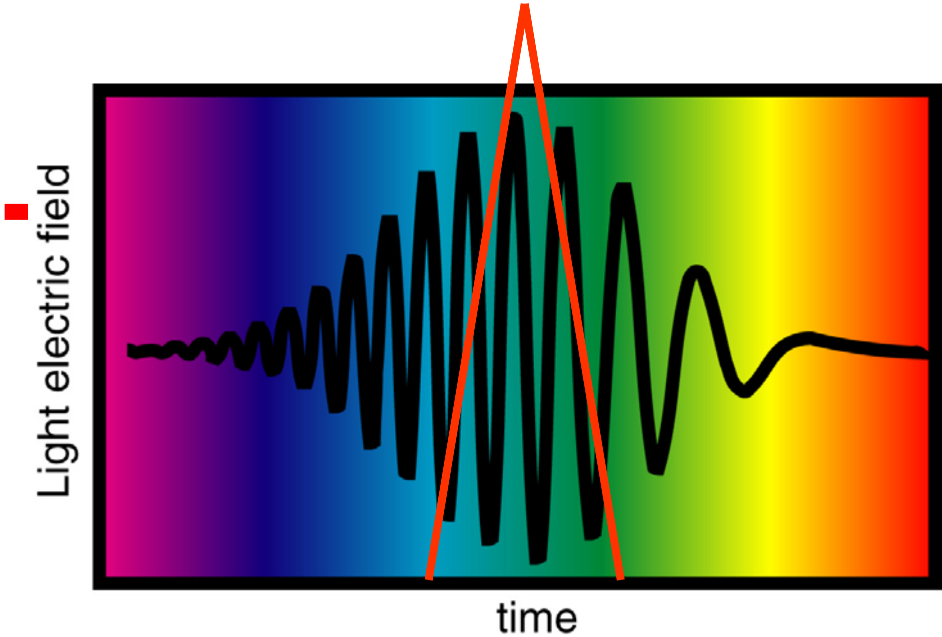



ATF Laser Oscillator-to-Clock Relative Phase [ps]
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
-2.1
-2.2
1/12/2001 16:00
1/12/2001 22:00
1/13/2001 4:00
1/13/2001 10:00
1/13/2001 16:00
1/13/2001 22:00
1/14/2001 4:00
1/14/2001 10:00
1/14/2001 16:00

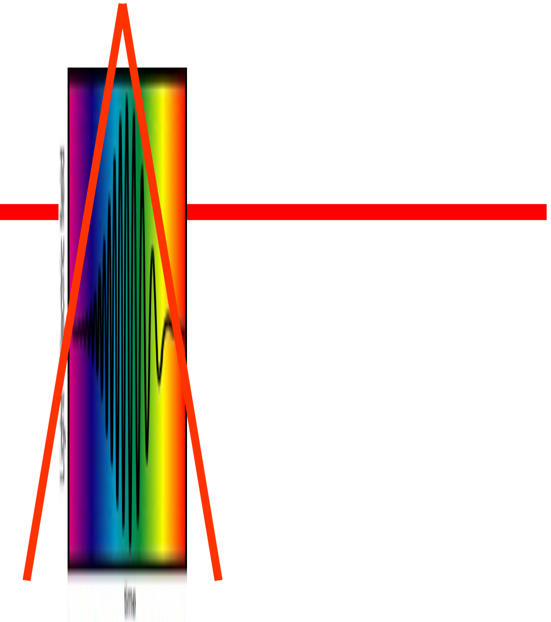
Jitter Measurement Technique Based on HGHG







$$\tau_{laser} \succ \tau_{e-beam}$$



$$\tau_{laser} \leq \tau_{e-beam}$$