WG6 Summary Viewgraphs

W. Leemans, LBNL

APRIL 6-9, 1999
ARGONNE NATIONAL LABORATORY, ARGONNE, IL U.S.A.

Titles of presentations

1. Dr. Todd Ditmire:
   Lawrence Livermore National Laboratory

   "High peak- and average-power ultrafast lasers and their application to femtosecond x-ray generation"

2. Dr. Igor Pogorelsky:
   Brookhaven National Laboratory

   "Gas Laser Technology for Future Laser Synchrotron Sources."

3. Dr. Tom Cowan:
   Lawrence Livermore National Laboratory

   "Short-pulse x-ray production by relativistic Thomson scattering"

4. Dr. Roman Tatchyn:
   Stanford Linear Accelerator Center

   "Free-Electron Radiation Sources Based on High-Contrast Energy Modulation of Electron Beams"

5. Dr. Sterling Backus:
   University of Michigan

   "Ultrafast Lasers and Laser-Based Coherent X-Ray Sources".

6. Dr. Eric Esarey:
   Lawrence Berkeley National Laboratory

   "Ultrashort electron beam generation in laser plasma accelerators".

7. Prof. Don Umstadter:
   University of Michigan

   "Ultrashort-duration x-rays from laser-plasmas".

8. Dr. Antonio Ting:
   Naval Research Laboratory

   "High Energy Electron Injection and Acceleration with Intense Short Pulse Lasers".

G. Mourou

R. Schoenlein

G. Travish

H. Baecke

G. Krafft

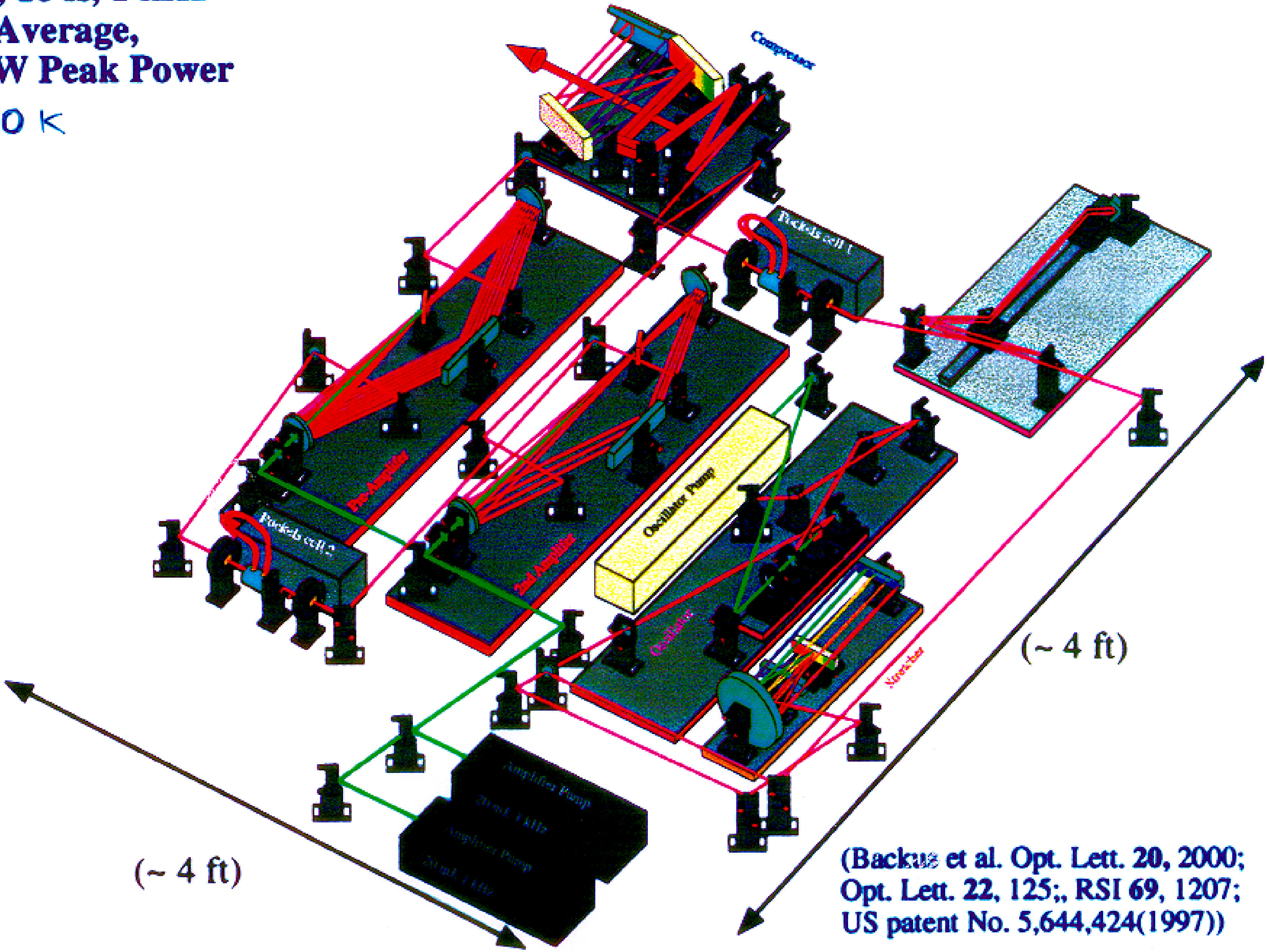
Laser systems

λ	Nd-glass	Ti:sap	FEL [redacted]	ATF-CO$_2$	projected (~ 5 yrs)
	1053 nm	800 nm	3-6 μm	10.6 μm	
E [J]	< 500 J	< 10 J ([illegible]) ~ 25 mJ	30 μJ	1 J 30 J	~ 10 J ~ 0.2 J
τ [fs]	> 400 fs	15-100 fs	> 370 fsec	150 ps 10 ps	~ 15 fs
rep. rate	< 1 shot/min /hr	10 Hz 1-10 kHz	37.5 MHz	0.03 Hz 0.1 Hz	1-200 kHz
P_{peak} [TW]	< 1 PW	< 100 TW < .5 TW	0.1 GW	6 GW 3 TW	~ 1 PW ~ 10 TW
P_{ave} [W]	NA	< 10 W < 15 W	1 kW	NA	~ 500 W
Synch w/ RF	1.3 ps	1 ps	< 1 psec	1 ps 1 ps	~ 300 fs

Present generation ultrafast lasers -

4.5 mJ, 16 fs, 1 kHz
4.5 W Average,
0.28 TW Peak Power

$250 K



(Backus et al. Opt. Lett. 20, 2000;
Opt. Lett. 22, 125;, RSI 69, 1207;
US patent No. 5,644,424(1997))

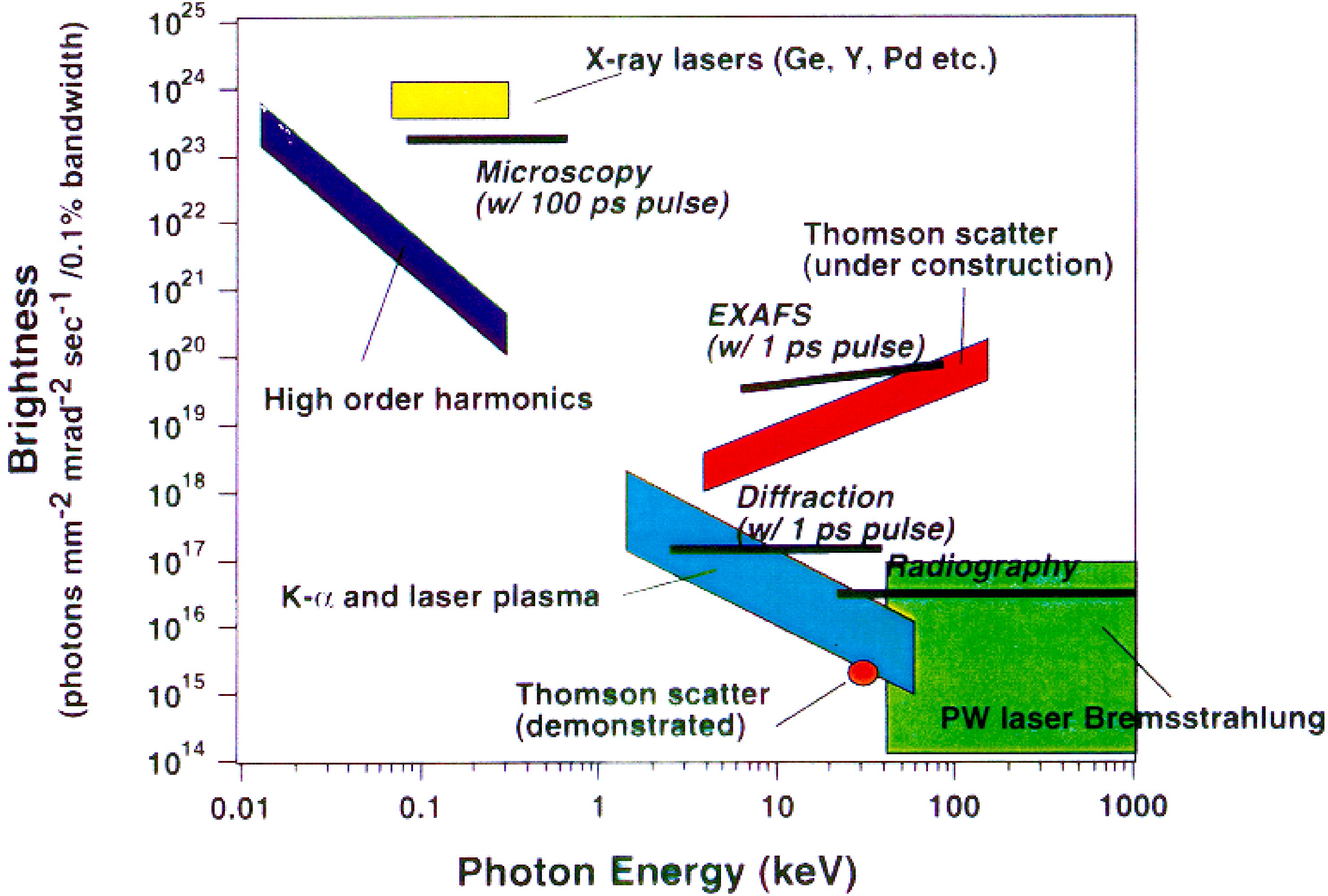
First Steps Toward Femtosecond X-Ray Sources

Several novel projects in an embryonic stage

- Thompson scattering of laser light from linac beam, and its future
- Time slicing of ALS stored beam, and its future
- Ring-based femtosecond x-ray sources?
- Laser plasma acceleration to generate short x-ray pulses

Can we make a useful femtosecond x-ray source?

The peak brightness of many laser-based x-ray sources will permit single shot experiments



We are integrating a 100 TW laser with a 100 MeV electron linear accelerator

Falcon Laser Specifications:

Pulse Energy: > 0.6 J
Pulse Width: 30 fs
Peak Power: ~ 20 TW
Repetition Rate: 1 Hz

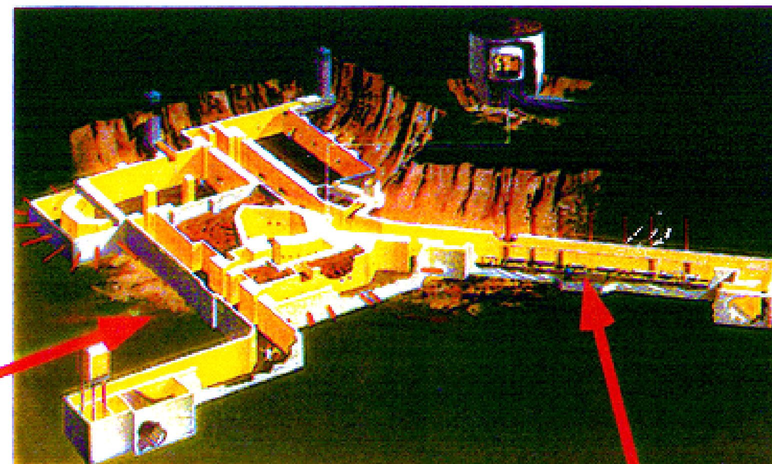
Focused Intensity: < 10^{20} W/cm^2

↕ temporally synchronized

LINAC Specifications:

Electron Energy: 100 MeV
Beam Emittance: < 2 π mm mrad
Electron Pulse Width: 1 ps
Charge per bunch: 1 nC

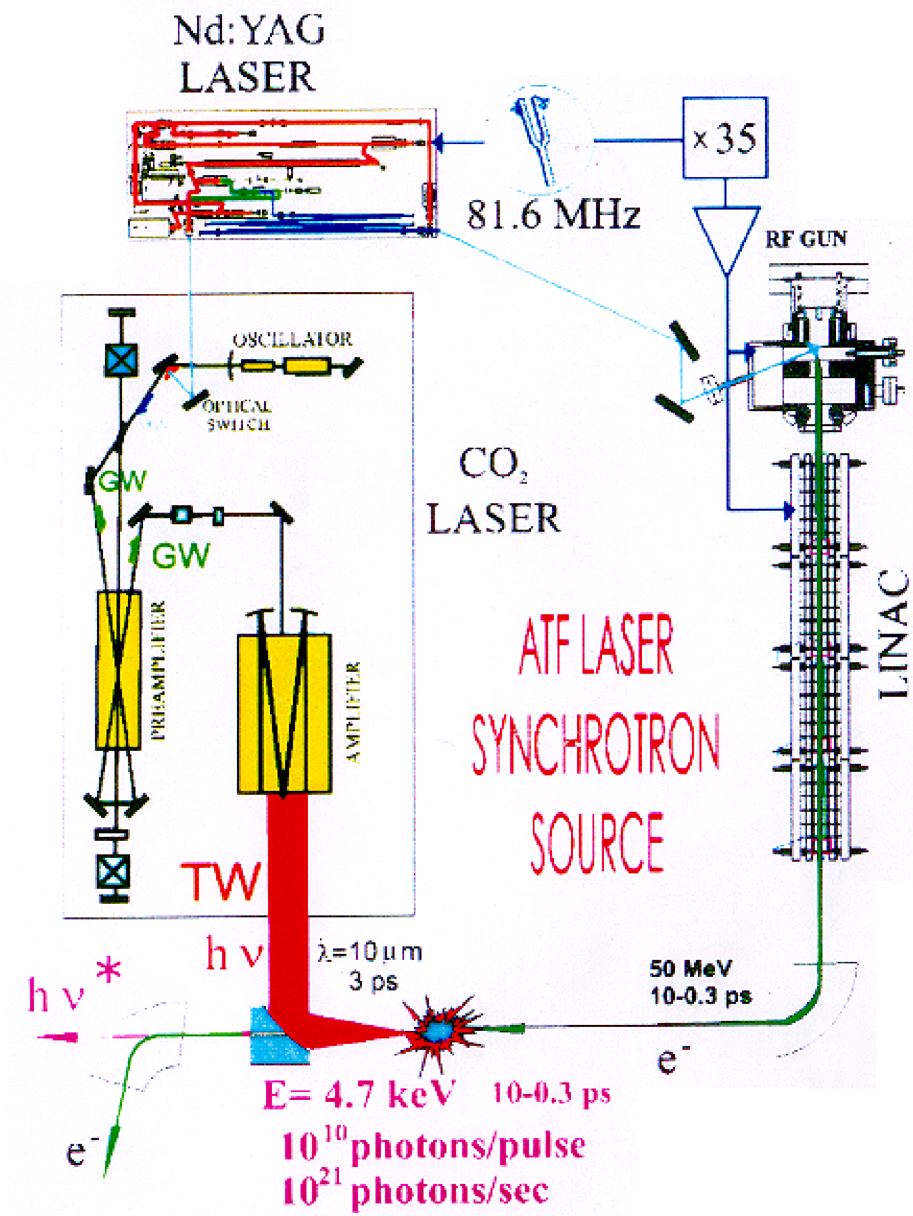
This facility will be completely unique in the US.

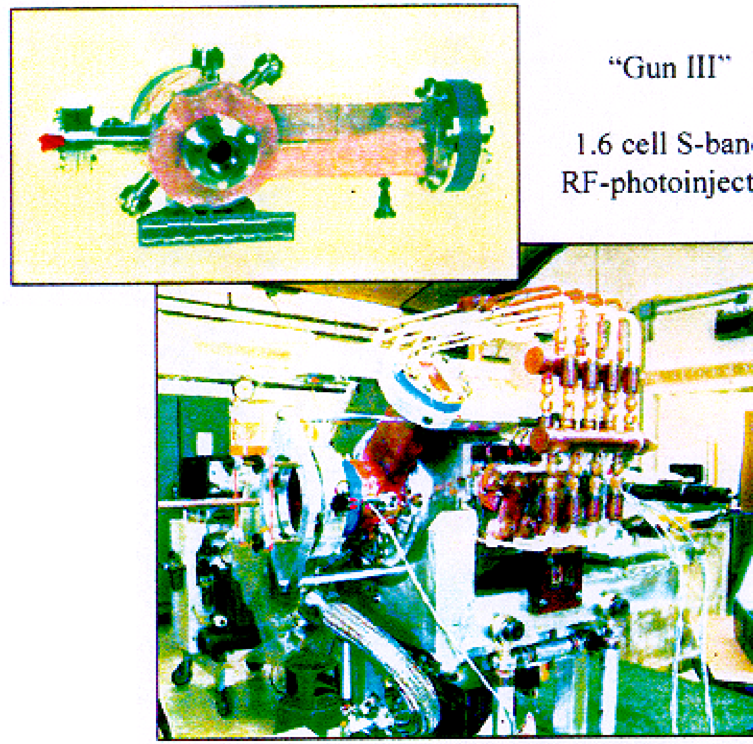


Falcon 100 TW Laser

Upgraded 100 MeV Linac

BNL-ATF Concept for an intense laser-electron x-ray facility

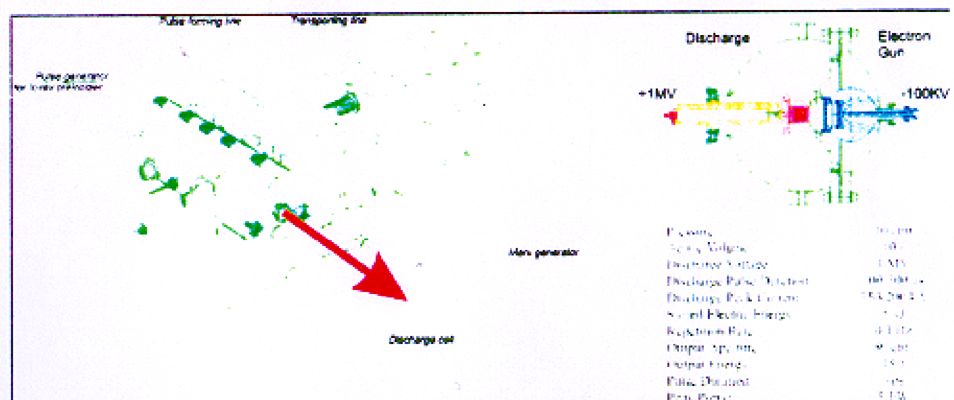




"Gun III"

1.6 cell S-band RF-photoinjector

5 TW, 3 ps (15 J) CO_2 Laser Upgrade

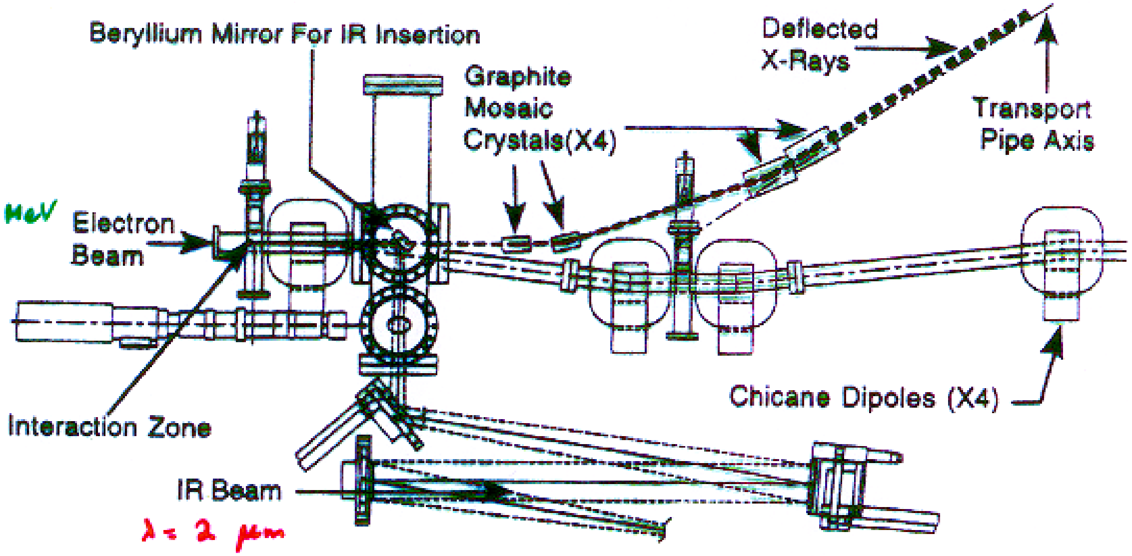


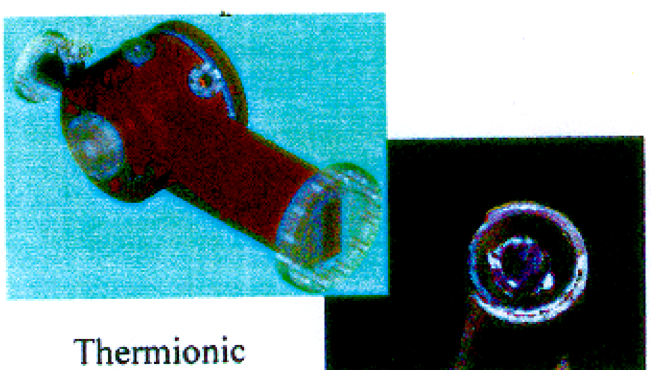
Vanderbilt FEL-based Compton X-ray Source

P.A. Tompkins, C. A. Brau, W.W. Dong, J.W. Waters (Dept. Phys., Vanderbilt Univ.)
F.E. Carroll, D.R. Pickens, R.R. Price (Dept. of Radiology, Vanderbilt Univ. Med. Center)

Above ground diagnostic and treatment rooms

10^6 /s

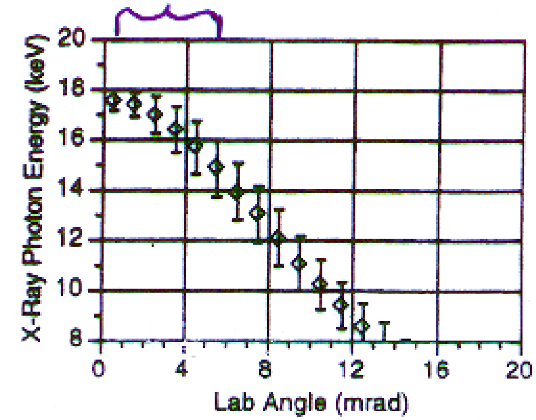




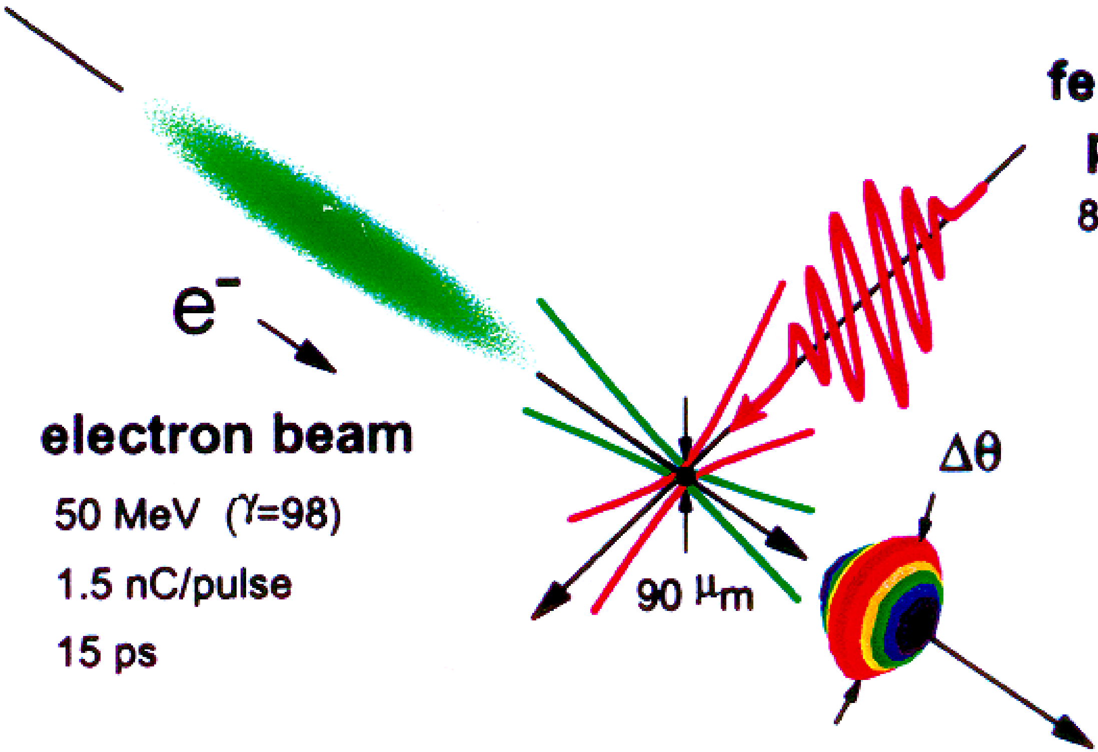
Thermionic RF-gun

- 20-40 A / 1 ps
  350 ps period
- 5 μs macropulse
- 30 Hz
  30-60 μA avg

10^8 s^{-1} produced.



90° Thomson Scattering



femtosecond laser pulse undulator

800 nm, 50 fs, 100 mJ

electron beam

50 MeV (γ=98)

1.5 nC/pulse

15 ps

femtosecond x-ray pulses

300 fs

0.4 Å (30 keV)

3×10^3 ph/sec/0.1% BW

(10^5 ph/pulse)

$\Delta\theta$ ~10 mrad

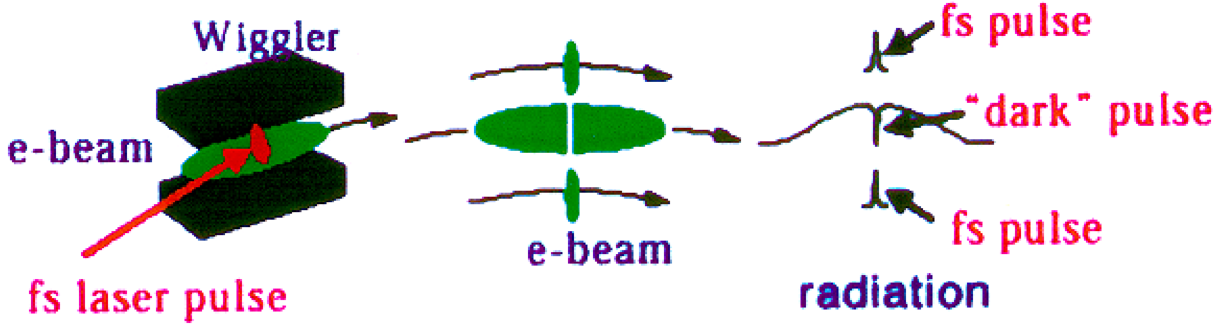
$$\lambda_x = \frac{\lambda_L}{2\gamma^2}$$

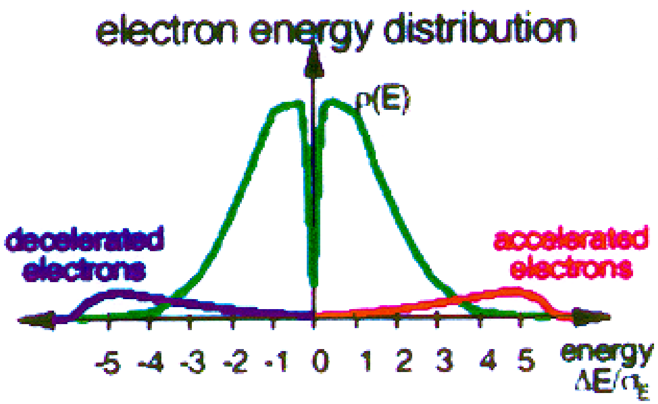
R.W. Schoenlein et al., Science, '96
W.P. Leemans et al., PRL '96, JQE '97

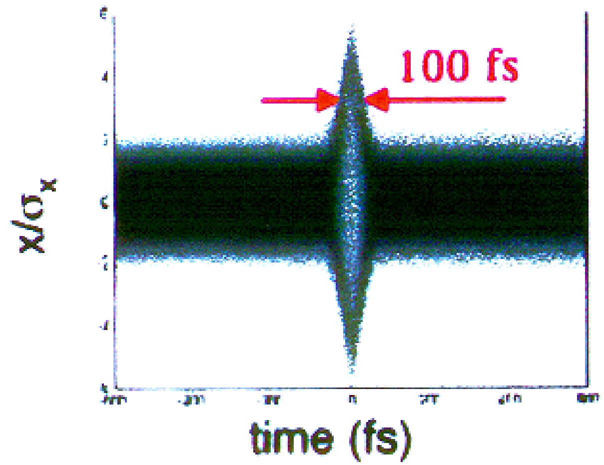
Thomson scattering: summary

- Hard x-ray generation from relatively low energy electron beams
- Ultra-short pulse duration
- Polarization control on fast time scale possible
  Chirp
- > 10^9 photons/pulse with present day laser/e-beam technology
- Laser probing of electron beams
- Experiments
  - LBNL (8 keV, 30 keV) use: time-resolved diffraction on InSb
    laser based diagnostic
  - NRL (0.5 keV) initial results reported by Ting et al.
  - LLNL, BNL (ATF), KEK: planned 10^4-10^5 increase in photon yield
  - TJNAF, Vanderbilt, Duke: FEL based, intracavity, high duty factor

S. Chattopadhyay
H.W. Chong
P. Heimann
T.E. Glover
R.W. Schoenlein
C.V. Shank
A. Zholents
M. Zolotorev







Flux:
10^7-10^8 p/sec
at 10% BW

FREE-ELECTRON RADIATION SOURCES BASED ON HIGH-CONTRAST ENERGY MODULATION OF ELECTRON BEAMS

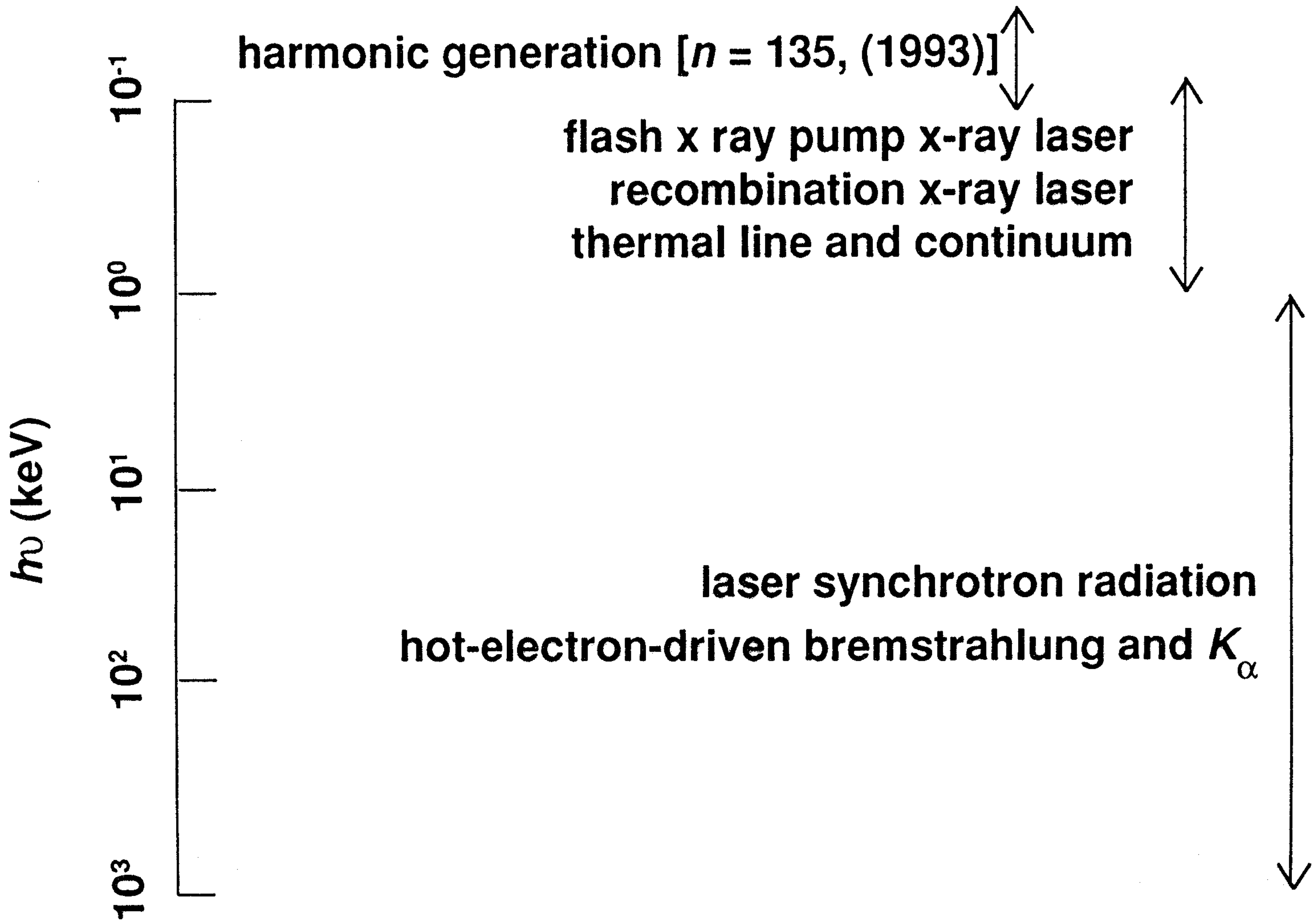
Roman Tatchyn
Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA

ABSTRACT

High-contrast energy modulation (HCM) of electron beams by high-power IR/visible/UV lasers can be achieved when the vector potential of the laser field (Kr) becomes comparable to that of the insertion device (Ku). Detailed theoretical studies of this parameter regime, conducted over the last several years [1,2,3] indicate that practical HCM configurations could be implemented with currently-available terawatt lasers [4], high-brightness electron beams in the 100+ MeV range [5], and low-intensity magnetic field synthesizers [6]. In this talk the basic physics of HCM and bunching, including simulations of collective dynamics in warm beams, will be briefly summarized, and a general comparison of HCM with FEL and Optical Klystron (OK) systems, including their radiative properties, will be presented. Selected novel directions for HCM research, in particular future-generation light source development, as well as possibilities toward reducing the size and cost of short-pulse X-ray FELs, will be introduced for workshop evaluation.

[1] R. Tatchyn, "Quantum Limited Temporal Pulse Generation," Proceedings of the Workshop on Fourth Generation Light Sources, M. Cornacchia and H. Winick, eds., SSRL Report 92/02, p. 482.
[2] R. Tatchyn, "Particle beam modulation techniques for the generation of subfemtosecond photon pulses in the VUV/soft X-ray range," NIM A 358, 56(1995).
[3] R. Tatchyn, "Principles of High-Contrast Energy Modulation and Microbunching of Electron Beams," presented at the FEL'98 Conference, Aug. 17, 1989, Williamsburg, VA; to be published in Nucl. Instrum. Meth., 1999.
[4] C. Le Blanc, E. Baubeau, F. Salin, J. A. Squier, C. P. J. Barty, C. Spielmann, "Toward a terawatt-kilohertz repetition-rate laser," IEEE Journal of Selected Topics in Quantum Electronics 4(2), 407(1998).
[5] J. F. Schmerge, D. A. Reis, M. Hernandez, D. D. Meyerhofer, R. H. Miller, A. D. T. Palmer, J. N. Weaver, H. Winick, D. Yeremian, "High brightness photoinjector development at the SLAC gun test facility," Nucl. Instrum. Meth. A407, (1998).
[6] R. Tatchyn, "Fourth Generation Insertion Devices: New Conceptual Directions, Applications, and Technologies," Proceedings of the Workshop on Fourth Generation Light Sources, M. Cornacchia and H. Winick, eds., SSRL Report 92/02, p. 417.

Mechanisms for the Generation of Ultrashort-Pulse X-Rays



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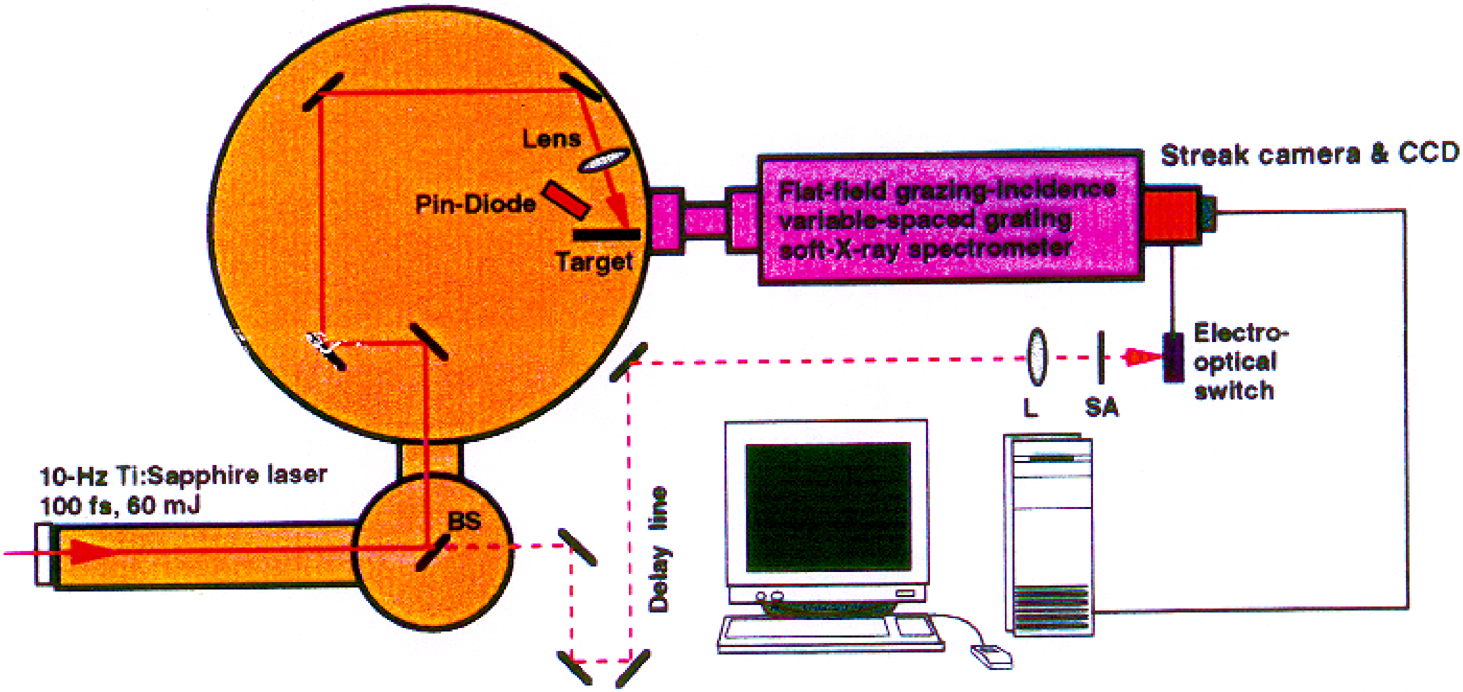
Center for Ultrafast Optical Science

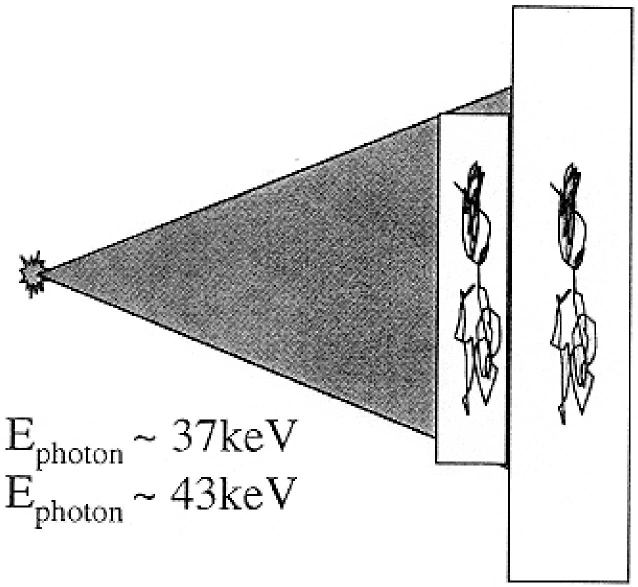
Experimental Geometry - Carbon

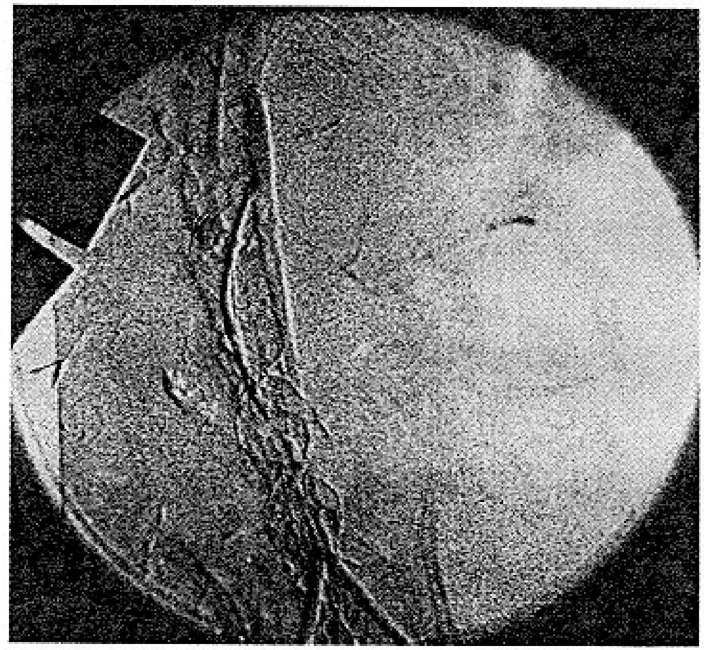


- High-contrast Ti:sapphire laser
  - deposition of laser energy at solid density
- Jitter-free accumulation through laser-triggered x-ray streak camera
  - higher signal
  - better signal-to-noize ration
  - Δt = 4 ps over up to 1200 shots in this configuration

Digital Energy Subtraction Imaging

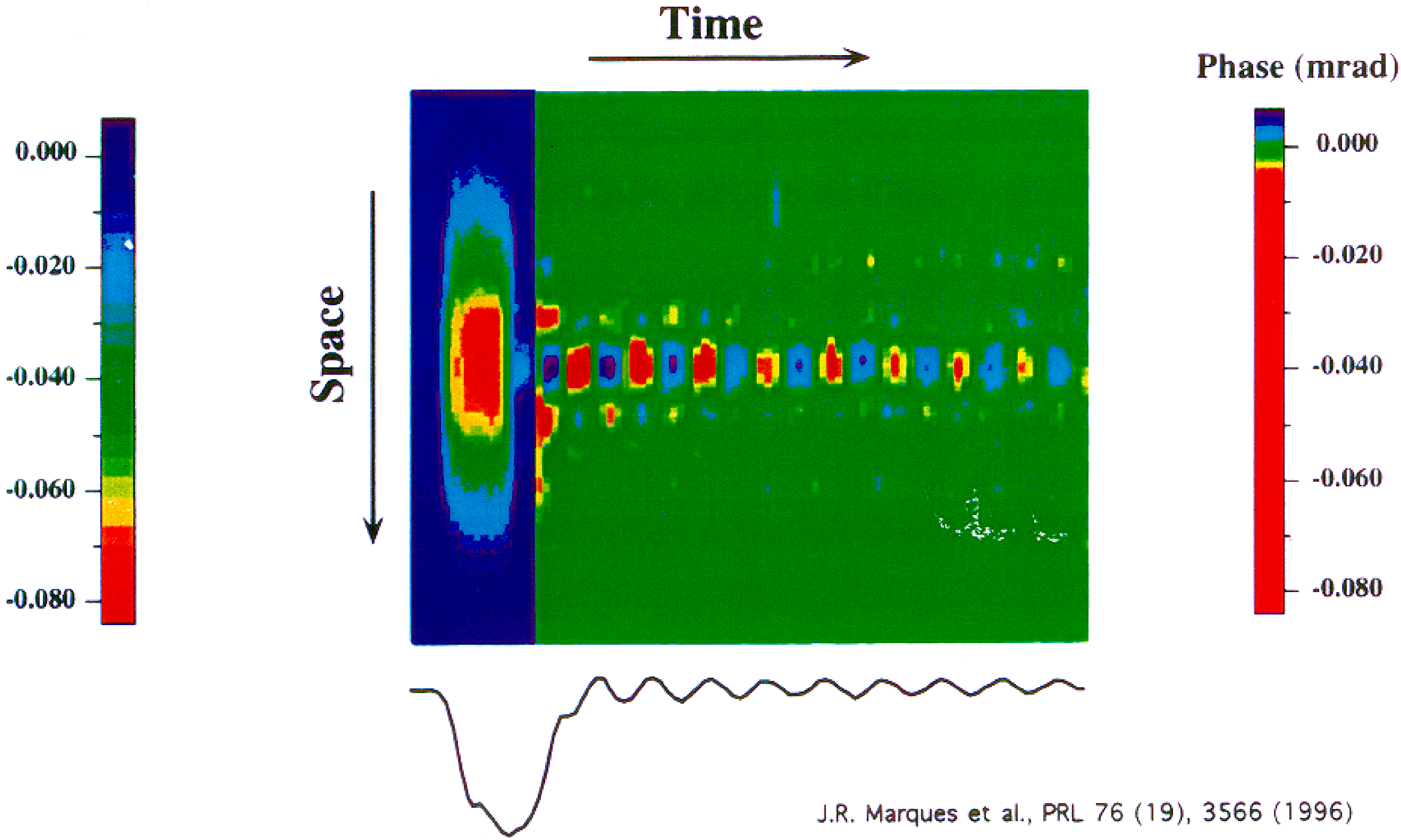
- potential application to cardiac angiography





J.C.Kieffer, Z.Jiang et al, INRS

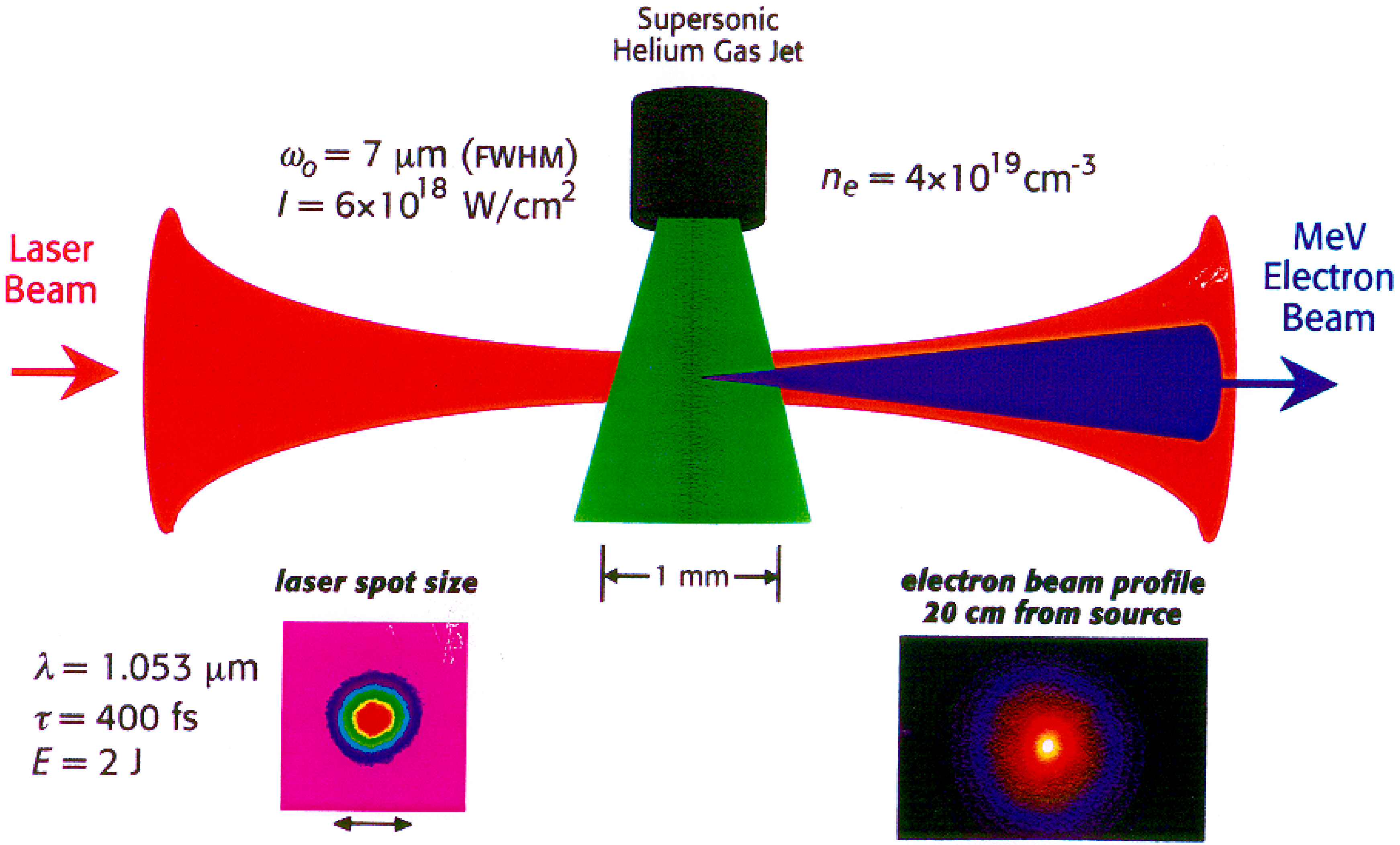
Electron density oscillation



J.R. Marques et al., PRL 76 (19), 3566 (1996)

Table-top accelerator creates energetic, ultrashort, and ultrabright electrons

A relativistic electron beam is created when an ultrashort (400 fs) laser pulse is focused into a jet of Helium gas. Under the right conditions, energetic electrons (1-40 MeV) emerge in a well-collimated beam. The acceleration occurs in less than 1 mm!



The Profile of the Electron Beam Shows Three Concentric Components

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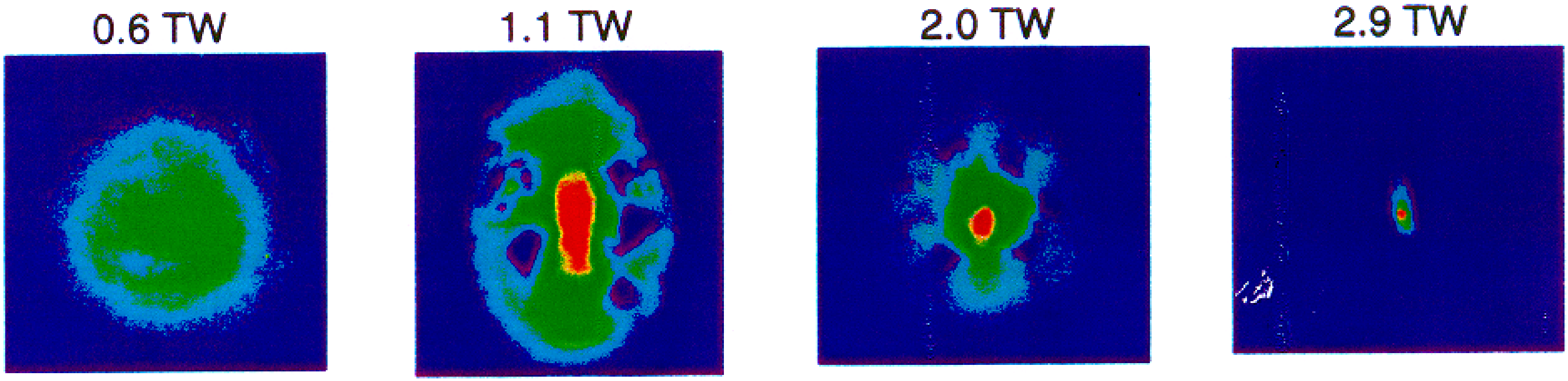
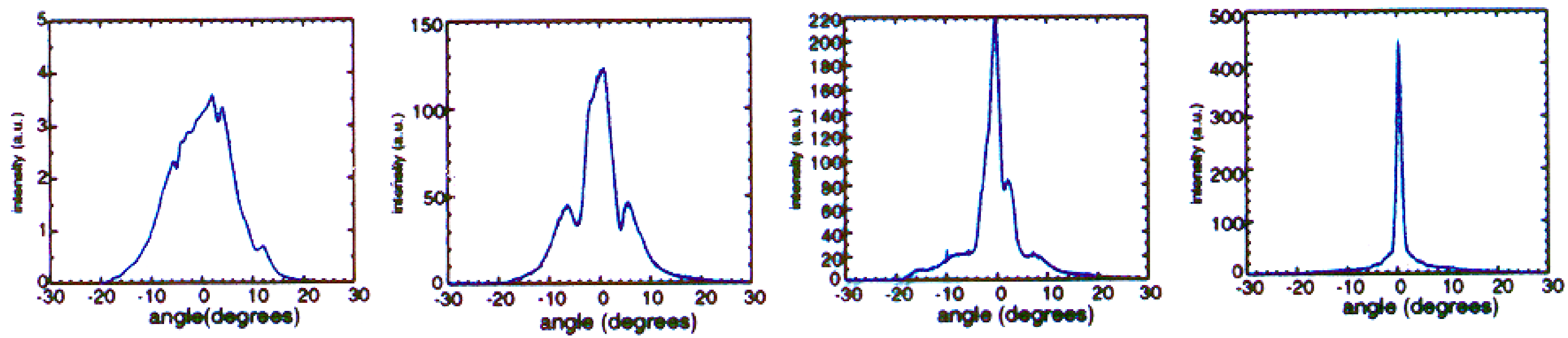
Variation of the electron beam profile with increase of laser power for $2.3 \times 10^{19}\ cm^{-3}$ plasma density



Horizontal lineouts through the center of the beam profiles



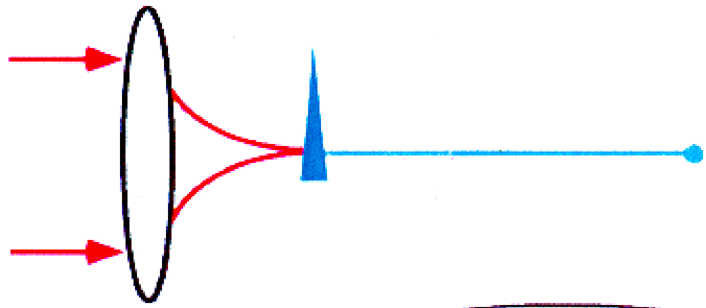
* The FWHM divergence angles of the 1st, 2nd, and 3rd components are 20°-25°, 5°-10°, and 1°-3°, respectively.
* Symmetric dark holes appear in the first beam component when the second beam component appears.

Advantages of Laser-Plasma Injectors

high-laser-beam intensity

=

low-particle-beam emittance



micron-size laser focal spots and pulse-lengths

ultra-high-field acceleration gradients

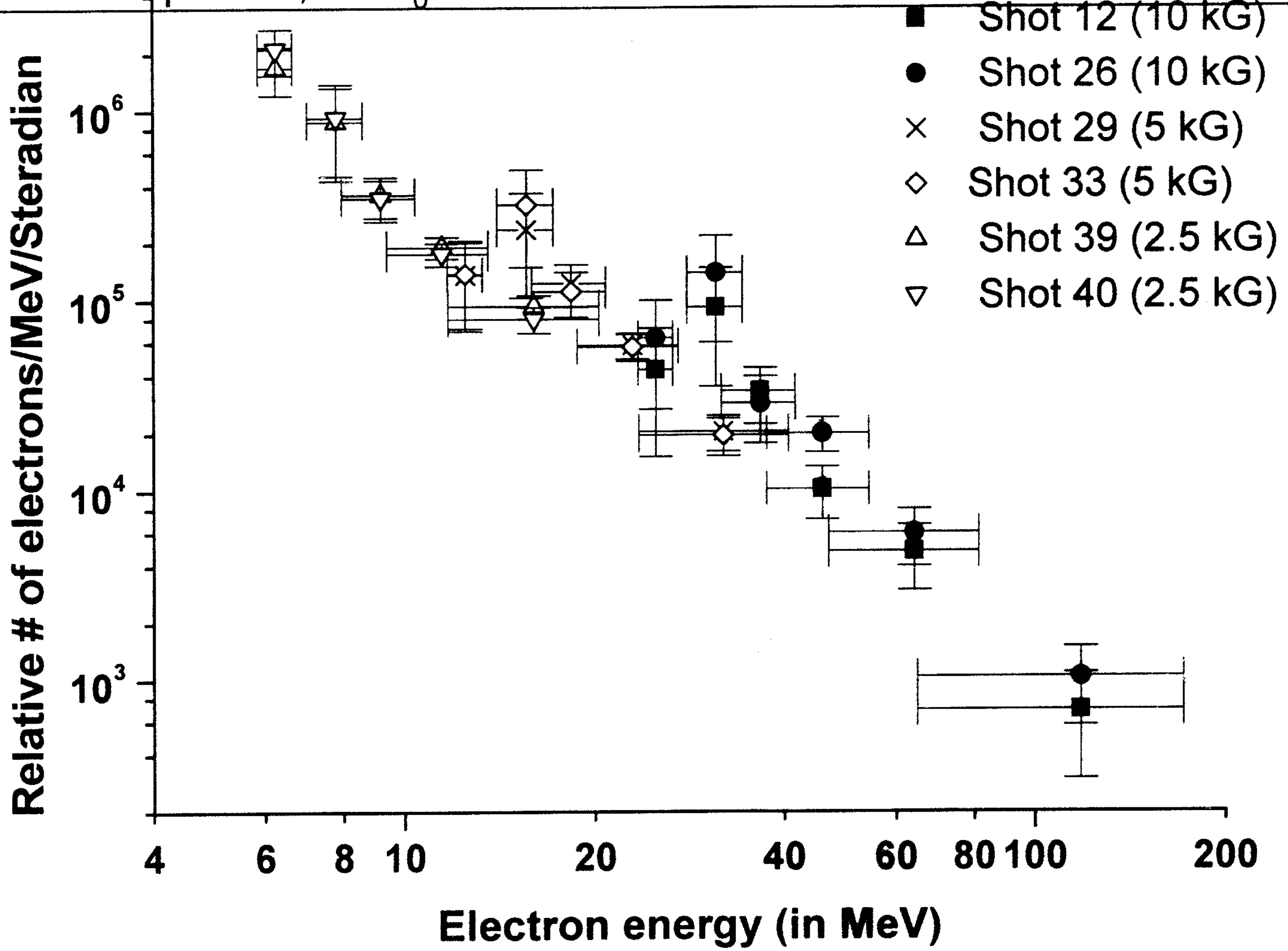
particle bunch is born with micron-scale dimensions

less time for space charge to act on particles before relativistic velocities are reached

particle beam emittance is preserved

Single shot electron energy spectra in the NRL SM-LWFA using a new multi-channel electron spectrometer

- Peak energy ~ 100 MeV
- Peak Acceleration field = 100-500 GV/m
- Wakefield Amplitude, $\Delta n/n_0 \approx 1$
- Electrons trapped in the wakefield by backward Raman scattering[1]



NRL
~100 MeV

Total e⁻
10^8-10^9

NRL

1 C.I. Moore *et al.*, *Phys. Rev. Lett.* **79**, 3909 (1997)

RAL/IC/UCLA (100 MeV), Michigan (40 MeV), Japan (>100 MeV)

Laser wakefield acceleration : all-optical injectors

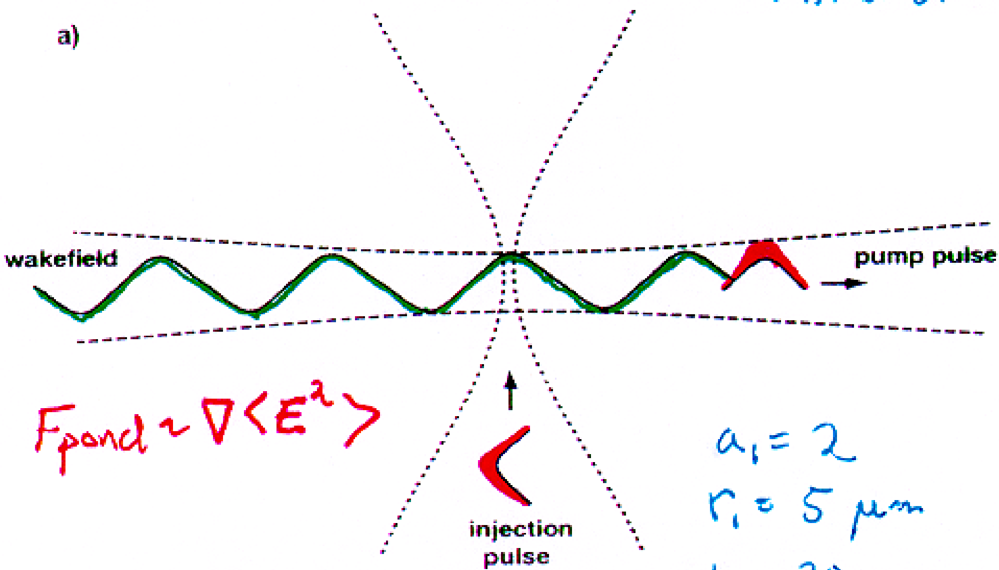
- Table-top, low cost source of high energy beam (10's of MeV's)
- Utilizes multi-terawatt laser systems
- fs bunch length, > pC/ bunch (kA peak current)

  $B_p \sim 10^7 - 10^9$ ph/s/mm^2-mrad^2/0.1%BW
- Synchronized with laser pulses at fs-level

- LILAC concept: Umstadter et al., PRL96
  Hemker et al., PRE 98
- Colliding pulse scheme: Esarey et al., PRL97
  Schroeder et al., PRE 99
- LIPA concept: Moore et al., PRL 99

LASER INJECTION

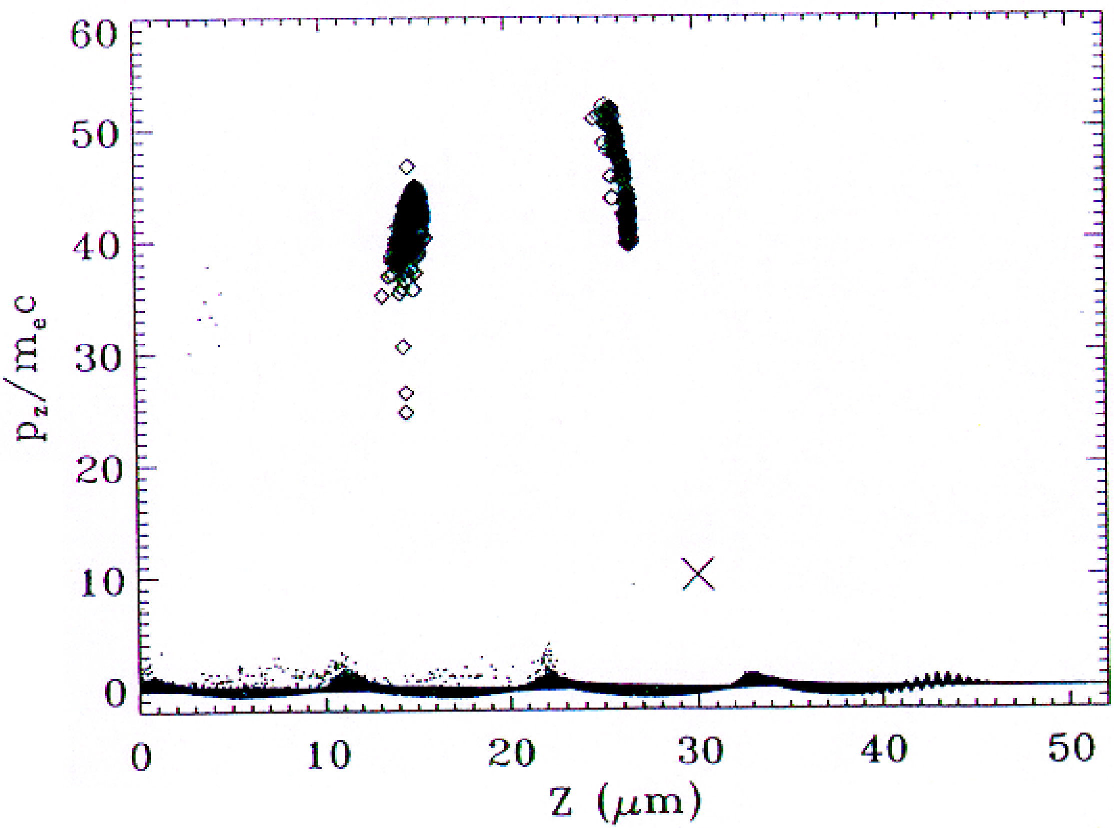
Umstadter et al PRL 96



$a_0 = 1.6$
$r_0 = 8\ \mu m$
$L_0 = 10\ \mu m$

$a_1 = 2$
$r_1 = 5\ \mu m$
$L_1 = 20\ \mu m$

$z = 100\ \mu m$, 2.3 GV/cm, $10^{19}\ cm^{-3}$

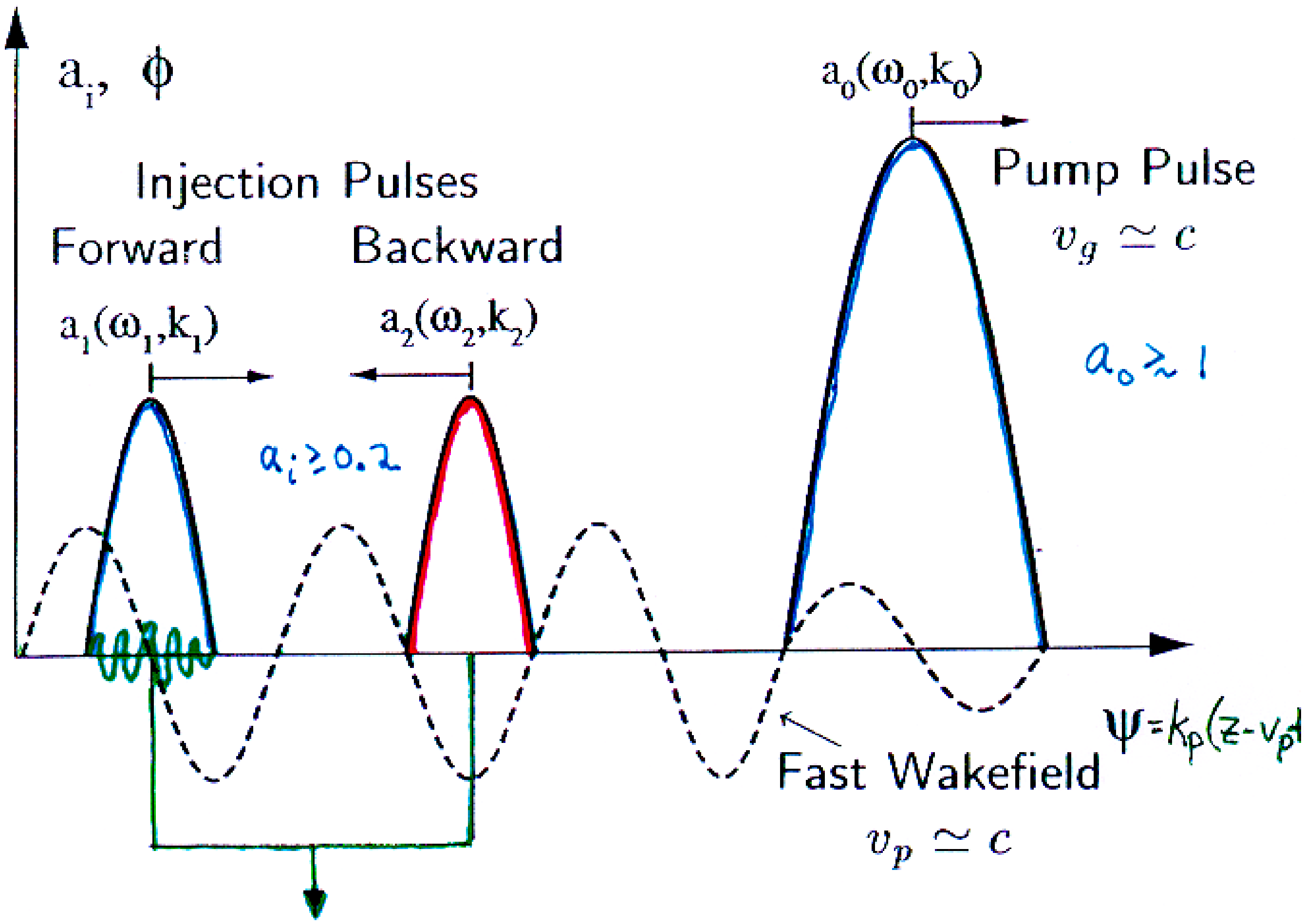


10 fs
23 MeV ±20%
2π mm-mrad
$3 \times 10^7\ e^-$

Laser Injection: Colliding Pulses

LBNL NRL

Esarey et al PRL (1997)



Slow Ponderomotive Beat Wave: $F_p \sim \partial(a_1 a_2)/\partial z$

$$F_p \sim (k_1 + k_2)\hat{a}_1\hat{a}_2 \cos\left[(k_1 + k_2)z - (\omega_1 - \omega_2)t\right]$$

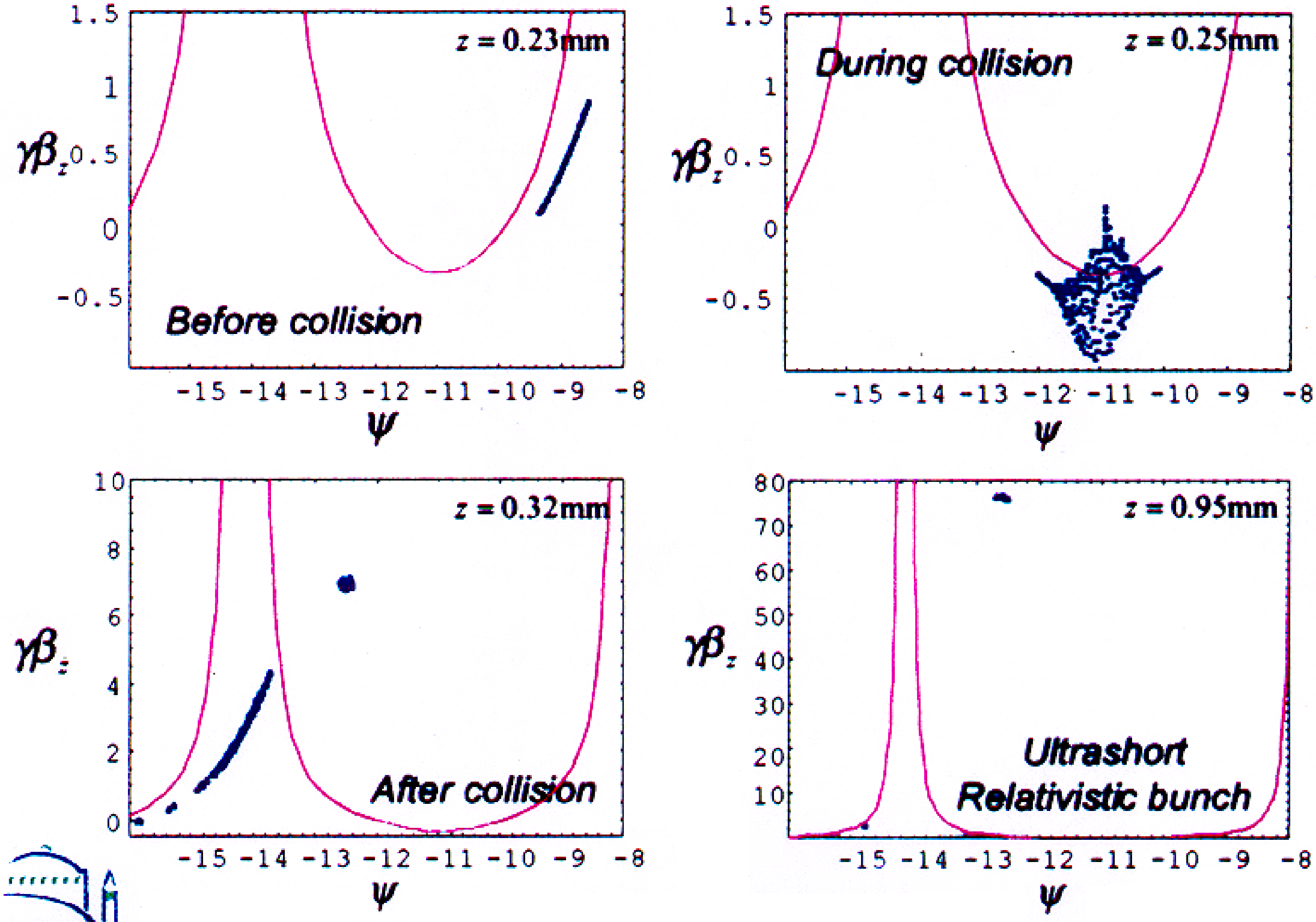
$$v_p = \frac{\omega_1 - \omega_2}{k_1 + k_2} \simeq \frac{\Delta\omega}{2k_0} \simeq \frac{\Delta\omega}{2\omega_0} c \ll c$$

$\left(\lambda_{beat} = \frac{\lambda_0}{2} \ll \lambda_p\right.$

1. Slow Beat Wave ($v_p \ll c$) → Initial Trapping + Heating
2. Fast Wakefield ($v_p \simeq c$) → Acceleration

Electron Orbits:

Longitudinal phase space evolution of distribution of plasma electrons



Mean energy = 39 MeV

Bunch duration = 1 fs

Energy spread = 0.08 MeV

C. B. Schroeder et al.

Conclusion

- Laser technology is an integral component of present ultra-short x-ray sources

- High brightness electron beams produced by laser driven photocathode guns

- High power laser systems will continue to be an essential part of next-generation light source research and a critical part for advanced accelerator development

- Near-term opportunity to explore scientific justification of ultra-fast science and dynamic probing of complex systems as a component of future light sources.