Free Electron Lasers and the Path to Understanding

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Offered as a Contribution to Our Understanding of How we Learn

- With the development of functional x-ray free electron lasers, FELs are now understood to represent key new tools for our understanding of matter at the atomic scale
- But how did we get to this point in the development of our understanding ?
- And if past is prologue, what further discoveries may lie before us ?

Stages of the Process

- Creation of a “learning environment”
- Impact of paradigm shifts and the creative destruction of old concepts
- Picking up the pieces to adapt to the new order of scientific thought
- Devising the technologies required for proof of principle experiments
- Role of initial experimental data in promoting new and sometimes unexpected understandings
- Refinement of physical models and supporting technologies
- Critical assessment of physical models suggest need for new paradigm shifts

The Learning Environment circa 1950 in Northern New Jersey

- The epoch from 1920 through 1950 had seen the widespread application of basic electron beam technology in almost all aspects of every day life and industry
- In addition, the epoch from 1936 - 1950 had seen breakthroughs in both the concepts and development of radical new electron beam-based sources of electromagnetic radiation
- Every-day life in the Silicon Valley of those years (the northeast corridor from Philadelphia to Boston) was permeated by the multiple roles of friends and family members in these enterprises

The Madey Brothers with Princeton Staff Member and Technology Mentor Howard Schrader

FROM EDISON TO COLOR TELEVISION: The University Library, drawing upon the unique collection of tubes and bulbs maintained by Howard P. Schrader, of Princeton Junction (right), is commemorating the 75th anniversary of the incandescent lamp and the beginnings of the electronic industry with an exhibition in the Princetoniana Room. Here Mr. Schrader, whose collection numbers more than 6,000 electron-type tubes and electric light bulbs, is conversing with two brother scientists, Julius and John Madey, of Clark, N. J., both of whom have recently been licensed as full-fledged radio operators. Schrader is holding the original R.C.A. color television tube, while 11-year old John, in front of a portrait of Thomas Edison, is displaying the original Lawrence Color Tube.

Other Environmental Influences

- Family interest in radio and electronics
- Circle of family business acquaintances including scientists and engineers from the nearby Bell Labs, patent attorneys, etc
- Easy access to the dumpsters of local microwave manufacturers and to “Radio Row” in NYC
- Easy access to local universities (Princeton, Columbia, Newark College of Engineering
- Widespread remnants of Edison’s research and manufacturing empire

The Emergence of Lasers and the Creative Destruction of Vacuum Electronics

- By 1950, further advances into the THz and optical regions seemed remote on fundamental grounds (coupling of ebeams to surrounding circuit elements, cathode current densities)
- Schawlow and Townes' descriptions of masers and lasers coupled with the new understanding of the Gaussian eigenmodes of free space offered a new approach to high frequency operation that was not constrained by the established limits to the capabilities of electron tubes

Disappearance of Academic and Research Opportunities

- With the development of the transistor by Schockley and Bardeen at Bell Labs and the demonstration of the first functional optical laser by Maiman, further work on vacuum electronic radiation sources came to a rapid halt
- Reflecting these developments, the Stanford Applied Physics and Engineering Departments shifted their focus from “vacuum state” microwave electronics to solid state physics and lasers in the early 1960’s
- There was thus no place left in 1965 at which I could pursue studies of the physics and technology of advanced vacuum electronic radiation sources

Why had Electron Devices Suddenly Become Obsolete ??

- What distinguished the new lasers from the prior electron beam based sources ?
  - amplification in lasers followed from the rate equations for emission and absorption and Einstein's discovery of stimulated emission
  - the transition rates of the quantum systems considered by Schawlow and Townes were all independent of phase
  - the discovery of the Gaussian eigenmodes of free space provided an alternative to the coupled "slow wave structures" of the prior electron devices

Was there a Free Electron Radiation Mechanism that Could Fulfill these Conditions?

- All the prior vacuum electronic radiation sources had relied on the “bunching” that evolved as a consequence of the electrons motion in phase space
- What was needed was a radiation mechanism in which the probabilities for radiation and absorption were independent of phase

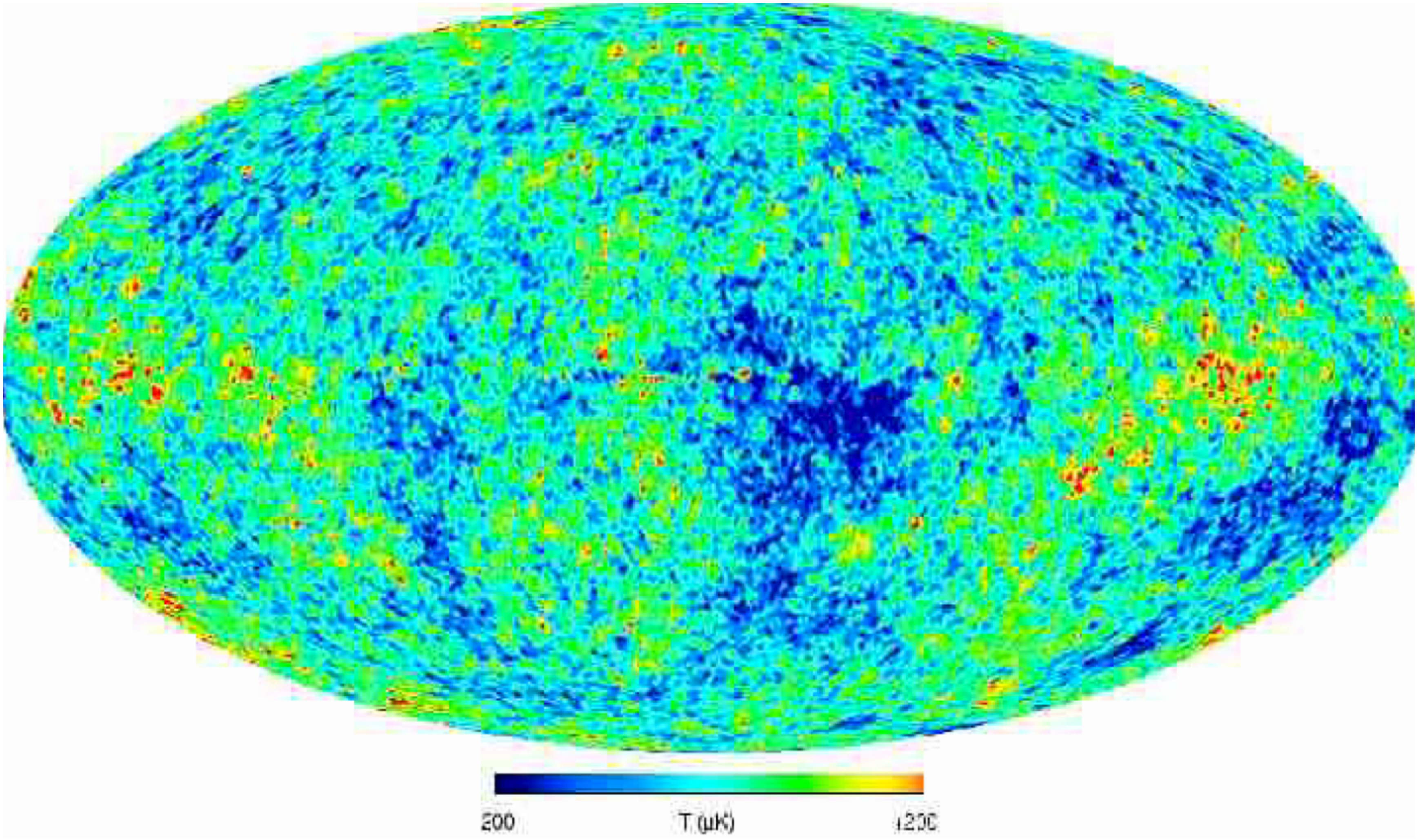
Compton Scattering Appeared as the Most Promising Candidate

- Assuming energy eigenstates for the initial electron and optical fields, neither the phase of the electrons or the optical field could be specified due to the uncertainty principle
- The methods of quantum electrodynamics for analysis of the transition rates per mode for this case were well known
- The finite momentum of the scattered quanta shifted the wavelengths for emission and absorption via the Compton effect

The Cosmic Black Body Radiation Existence Proof

- Dreicer’s analysis of the role played by stimulated Compton scattering in the thermalization of the cosmic fireball lent confidence to the existence of the effect
- But did this mean that we would have to re-create the conditions that prevailed in the early universe to demonstrate the effect in the Laboratory ??

WMAP Measurements of Thermalized Cosmic Black Body Radiation



What May Have Been Straightforward in the Early Universe Would Not be Easy in the Lab

- The Compton scattering cross section is proportional to $r_0^2 \sim 10^{-26}$ cm^2
- Unprecedented photon and electron beam densities are required to achieve transition rates relevant to laboratory experiments

Solving the Transition Rate Problem (1)

- Use of relativistic electrons, whose scattered radiation is confined to a 1/gamma cone in the forward direction, drastically reducing the number of modes into which that radiation was emitted
- Use of Compton backscattering from a relativistic electron beam would also make the laser completely tunable !!
- Relativistic electrons can also not tell the difference between real and virtual incident photons, permitting the substitution of a strong, periodic transverse magnetic field for the usual counter-propagating real photon beam

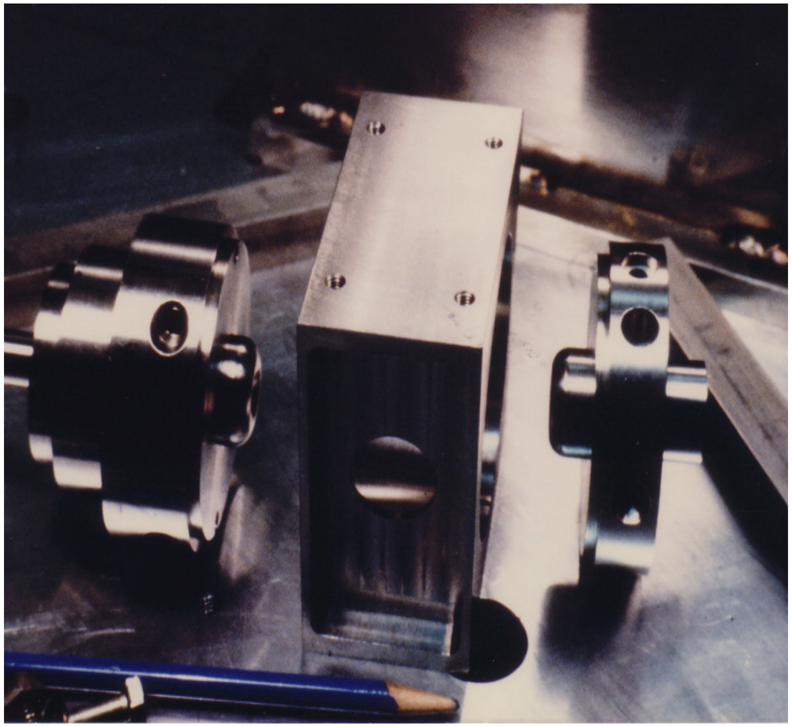
Solving the Transition Rate Problem (2)

- But there was no easy fix available to increase the volume density of the participating electrons to the level required to yield measurable (and ultimately useful) amplification factors
- So the key technical step in the laboratory demonstration of the proposed effect was the development of new means to generate the unprecedented high peak current, low energy spread and low angular divergence electron beams required to generate useable transition rates

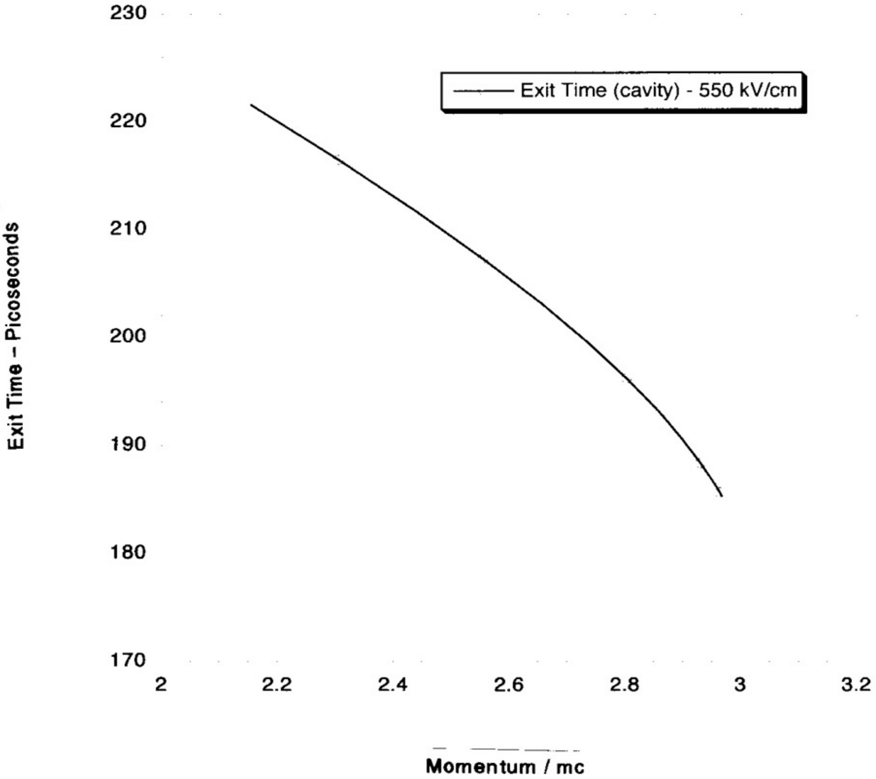
Pioneering Steps in Achieving the High Peak Currents Required for Laboratory Experiments

- Development of fast (nanosecond) pulsed dc electron guns to achieve ampere level peak currents for the first demonstrations of laser amplification at Stanford
- Development of thermionic microwave guns at Stanford to achieve the 40 amp peak currents required for useful infrared FEL oscillators
- Development of photoemissive microwave guns at Stanford to achieve the 125 amp peak currents required for the first high gain FEL system

Key role of Non-linear Magnetic Bunching in the Operation of Microwave Guns (1)

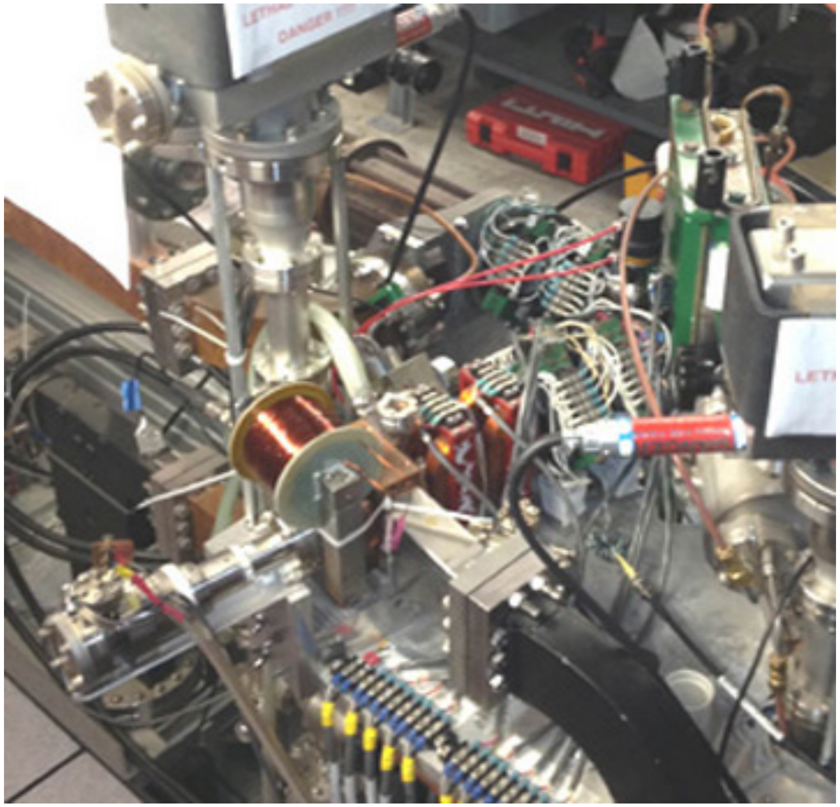


S-band gun cavity assembly

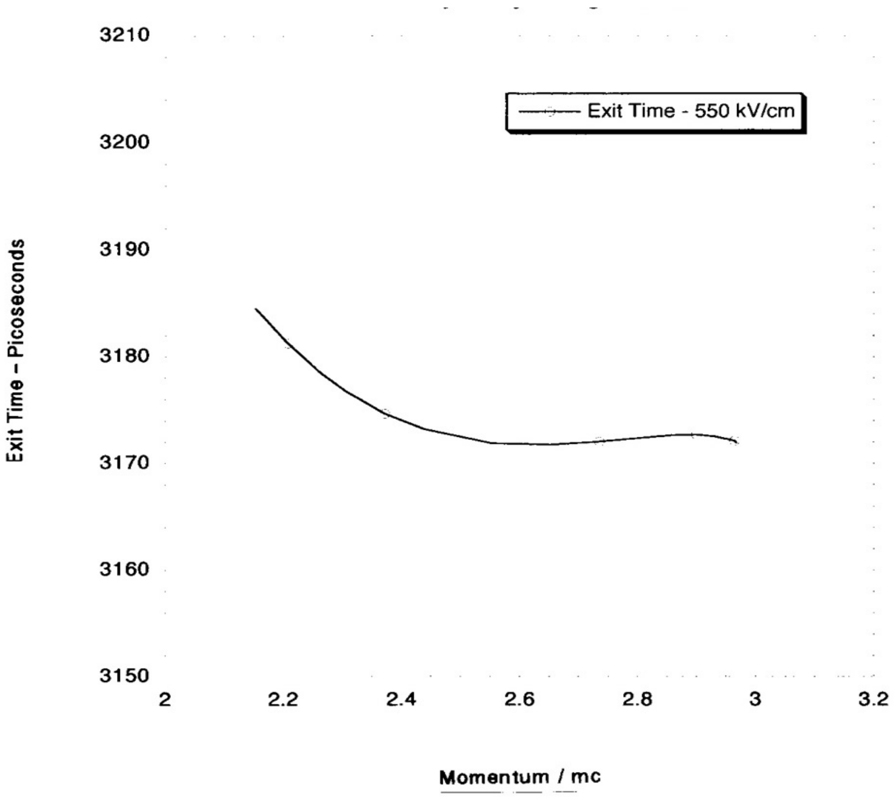


Cavity Transit time vs.Momentum

Key role of Non-linear Magnetic Bunching in the Operation of Microwave Guns (2)

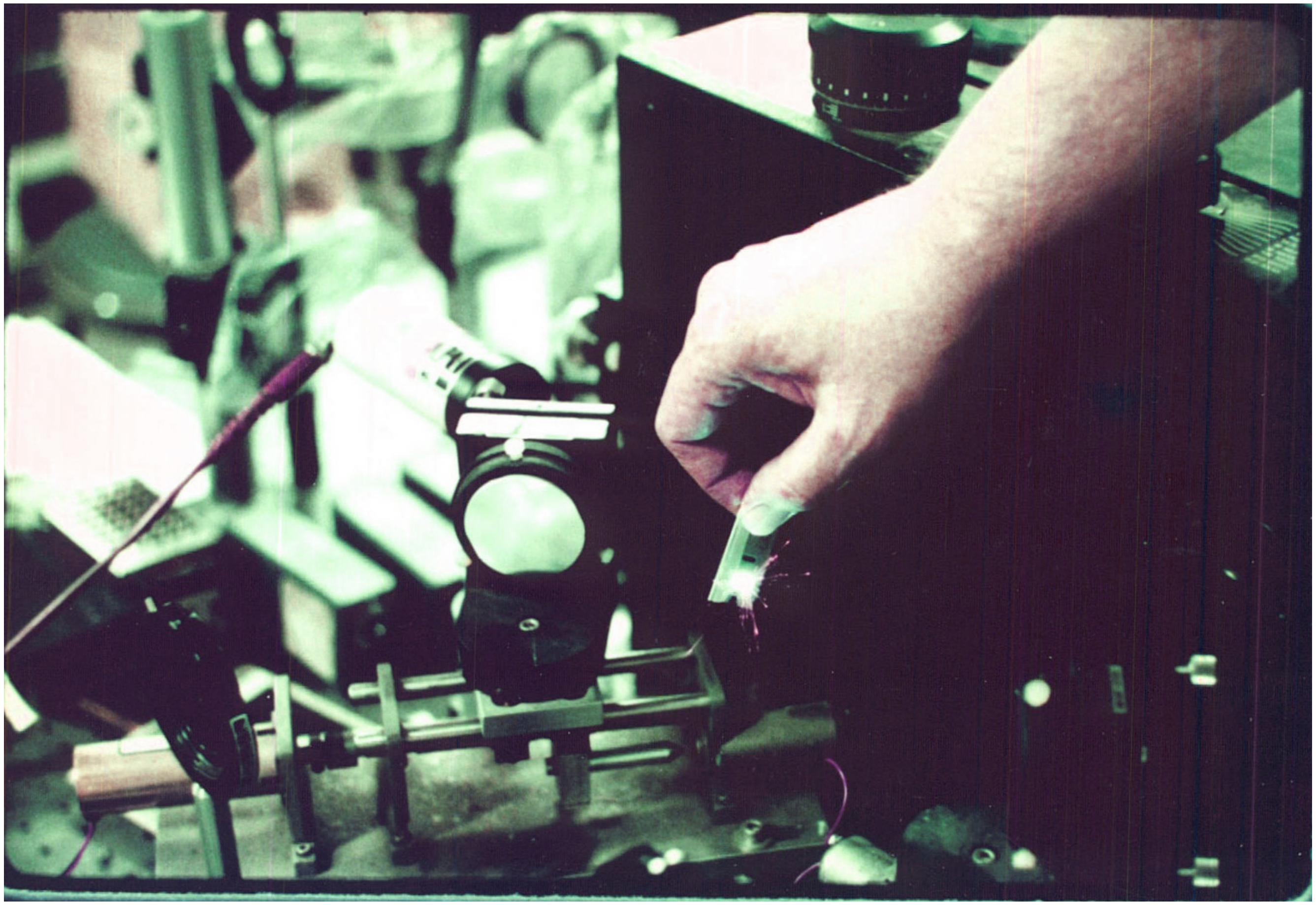


Gun system including Alpha magnet and drift tubes



Net Transit time vs. Momentum

High Rep Rate of S-Band Microwave Guns Enabled 100+ mJ Microsecond Pulses



Pulsed-mode Operation Enables New Surgical Procedures !

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Free Electron Laser

Laser light from Free-Electron Laser used for first time in human surgery

by David F. Salisbury

Laser light with a precise wavelength of 6.45 microns has an invisible kind of magic. It can slice through soft tissue coolly and cleanly, with less collateral damage than the sharpest steel scalpel.

Researchers at

Photos by Dana Johnson

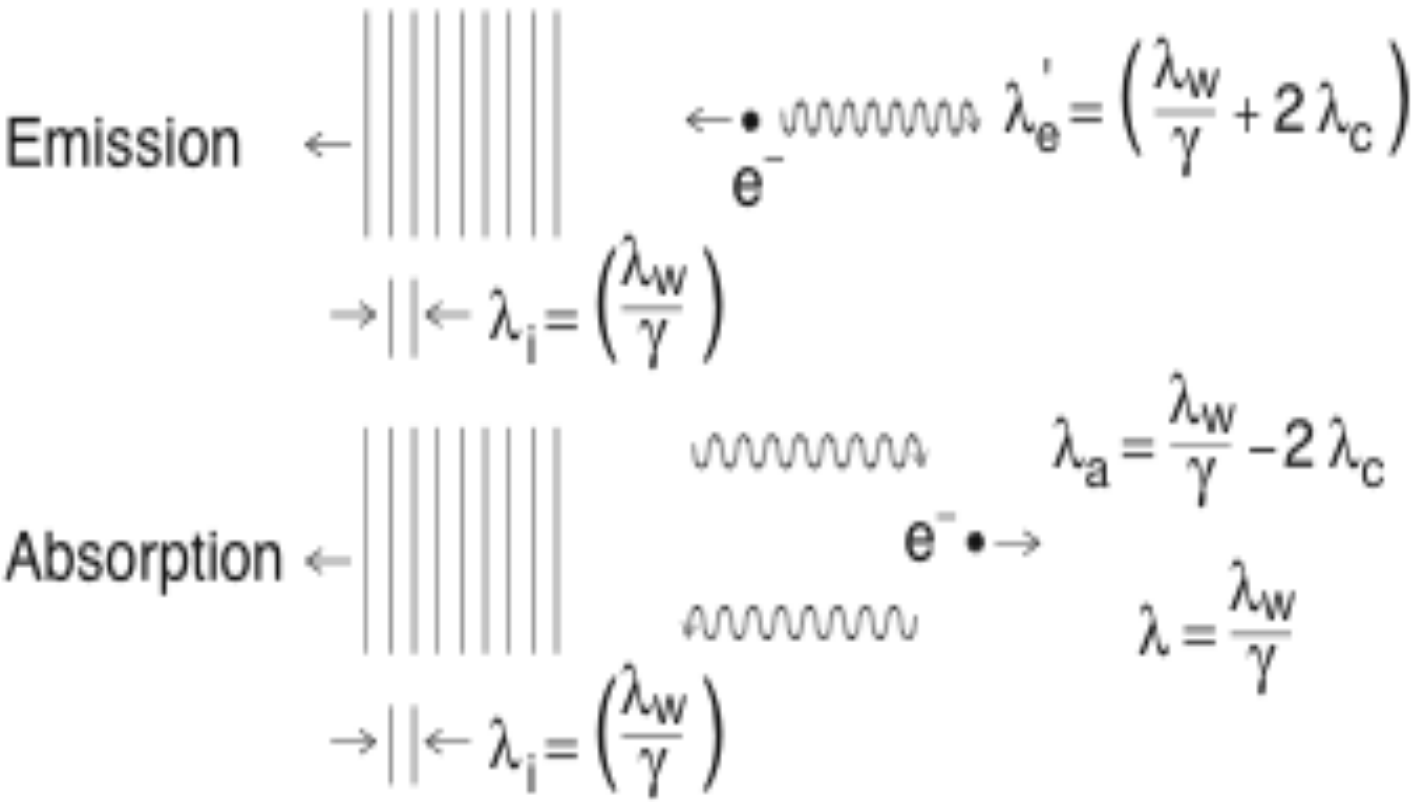
Dr. Michael Copeland talks with patient Virginia Whitaker, 78, of Kansas City, Mo., about using the FEL to remove her brain tumor.

(The FEL used by Vanderbilt was a clone of the Stanford MkIII System including its microwave electron gun)

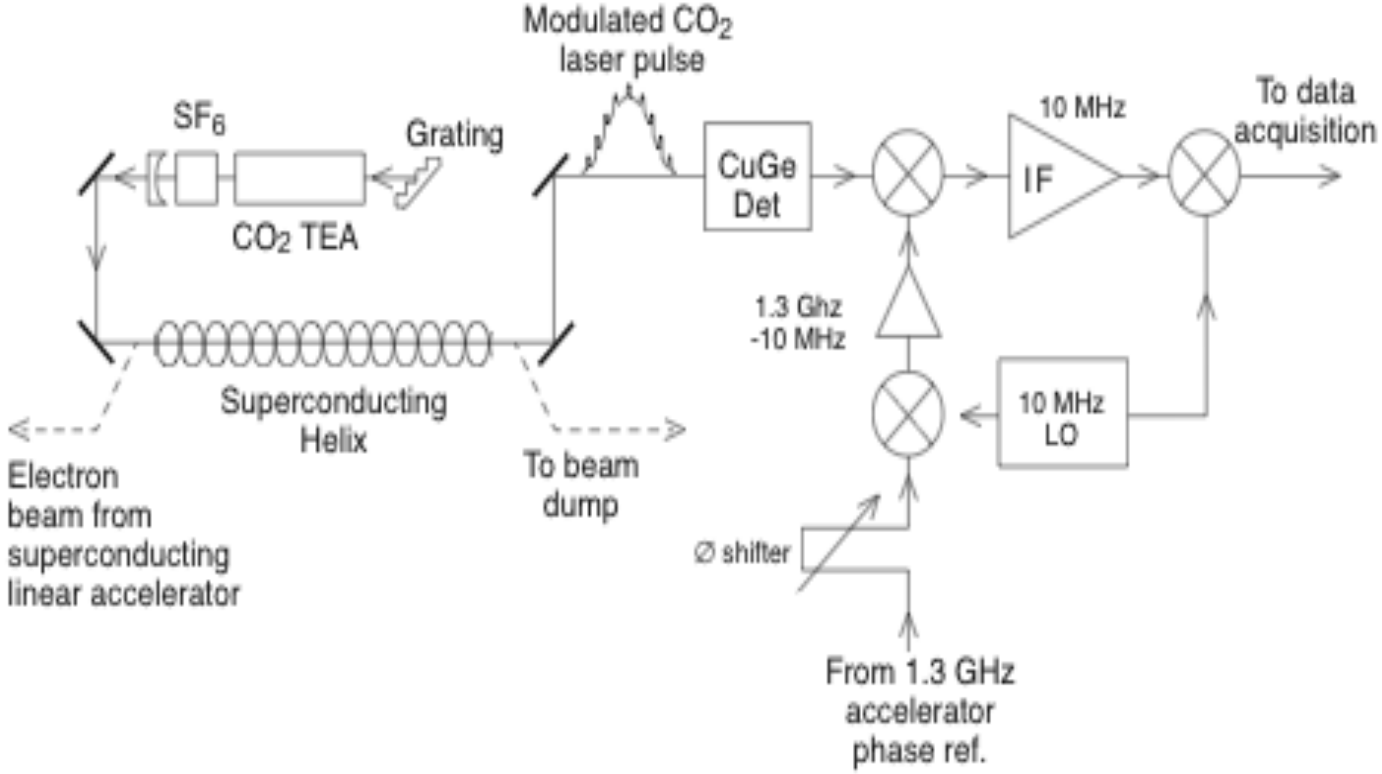
Key role of Necessity

- Limited funds for new device development made it impossible to pursue conventional approaches to high peak current ebeam sources
- The thermionic and photoemissive microwave gun concepts were high risk ventures that could only be justified by their low cost
- The project had the advantage of access to both the junkyard of accelerator equipment that had been accumulated in Stanford’s W. W. Hansen Laboratories over the prior 25 years and the advanced new superconducting accelerator being developed to replace that earlier equipment

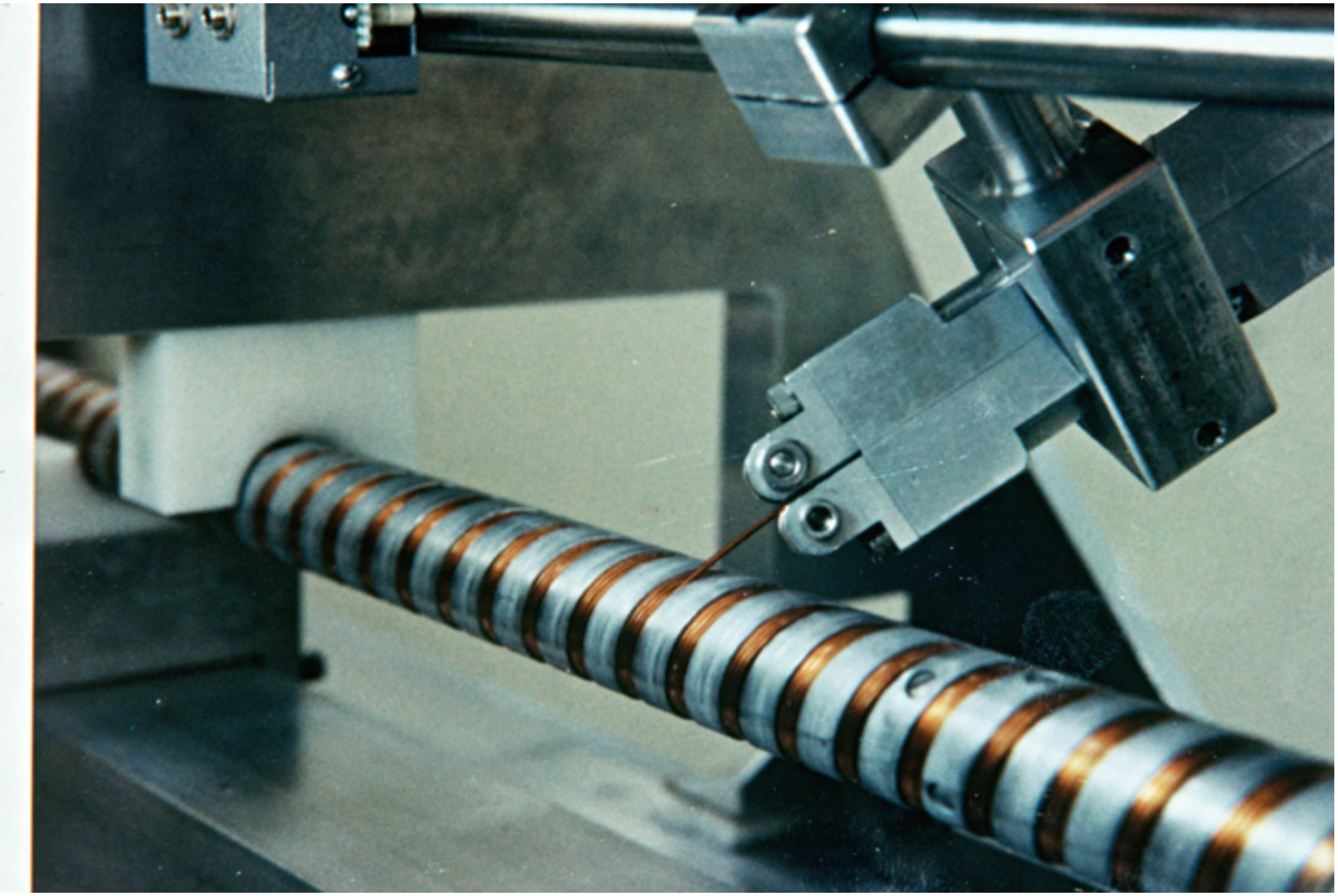
Basis of Amplification (as per Dreicer's analysis of Cosmic Black Body Radiation)



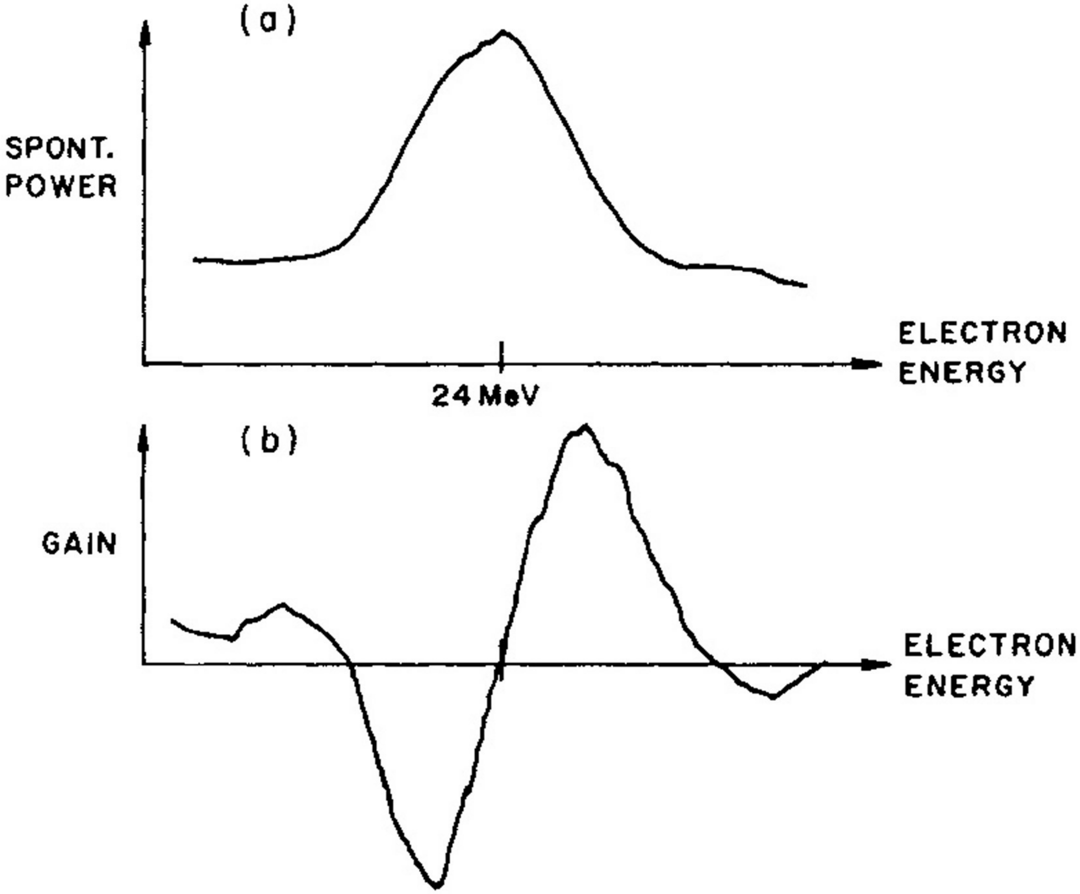
Amplifier Experiment Setup



Winding the Superconducting Helix



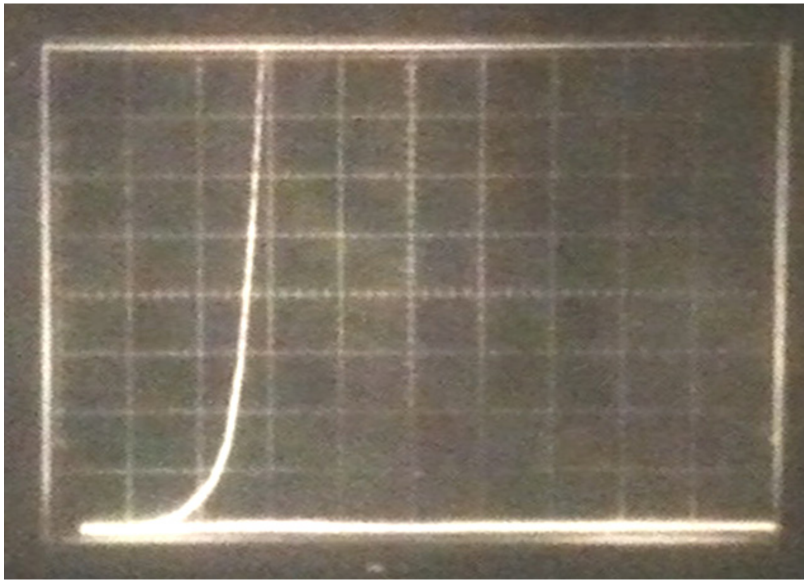
Gain Measured in Amplifier Experiment Exactly Matches Theory



Output Power of First FEL Oscillator Experiment (1977)

Observation of First Light

Stanford Laser Photocathode Microwave Gun Enables 150% gain/pass in 1988



FEL power output vs. time in the 1988 demonstration of the operation of the Stanford microwave gun in the photo-emissive mode

FIRST DEMONSTRATION OF A FREE-ELECTRON LASER DRIVEN BY ELECTRONS FROM A LASER-IRRADIATED PHOTOCATHODE

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We report the results from the first operation of a free electron laser (FEL) driven by an electron beam from a laser-irradiated photocathode. The Rocketdyne/Stanford FEL achieved sustained oscillations, lasting in excess of three hours, driven by photoelectrons accelerated by the Stanford Mark III radiofrequency linac. A LaB$_6$ cathode, irradiated by a tripled Nd:Yag mode-locked drive laser was the source of photoelectrons. The drive laser, operating at 95.2 MHz, was phase-locked to the 30th subharmonic of the S-band linac. Peak currents in excess of 125 A were observed and delivered to the Rocketdyne 2 m undulator which was operated as a stand-alone oscillator. Sustainable small-signal gain of 100% per pass was observed over a 2 h time period with periodic observation of small-signal gain as high as 150% per pass. Preliminary estimates of the electron-beam brightness deliverable to the undulator range from 3.5×10^{11} to 5.0×10^{11} A/(rad m)^2.

1. Introduction

Linac-driven free electron lasers, high-power synchrotron-radiation sources and high-power microwave devices all benefit from higher-brightness electron beams. In particular, advancement of FEL technology toward operating regimes characterized by shorter wavelength and higher power hinges on finding suitable electron-beam sources that can produce high-brightness, high-current beams. Conventional electron sources consist of a thermionic cathode positioned within a dc or rf electron gun, followed by either a subharmonic or magnetic bunching element, used primarily to increase peak current, and matching optics to preserve beam brightness into the accelerator. Recently, laser-illuminated photoemitters have emerged as an alternative to conventional thermionic sources [1,2]. Photocathodes have three significant advantages over thermionic cathodes:

(1) photocathodes produce intrinsically brighter electron beams [3],
(2) photocathode gun systems offer controlled time gating of the charge emitted from the cathode,
(3) photocathode gun systems provide a means of controlling the charge density profile at the cathode so as to maximize beam brightness at the undulator.

For rf-linac driven FELs, a train of low-emittance, high-peak-current pulses are converted to high-fluence optical pulses possessing similar temporal characteristics via the interaction of the electron beam pulses and undulator magnetic field. Typical pulse formats associated with rf-linacs are micropulse lengths between 1 and 100 ps separated by 0.35–250 ns over macropulse lengths of 5 100 μs. Pulse formats characteristic of rf linacs are easily replicated by lasers used to drive photocathodes, and thus allow a range of experiments which can shape initial electron-beam phase space to exploit any correlations which may prove beneficial to FEL performance.

2. System description

The FEL facility at the Stanford Photon Research Laboratory consists of a microwave gun [4] feeding the Mark III rf-linac [5] which is capable of accelerating electrons to approximately 40 MeV. Electrons are emitted by a 3 mm diameter LaB$_6$ cathode which is typically operated at 1800 K as a thermionic electron source. In the experiment reported here we irradiated the LaB$_6$ with 40 mJ, 100 ps laser pulses at 355 nm. The drive laser was a tripled Nd:Yag operating at 95.2 MHz which was phase-locked to the 30th subharmonic of the Mark III linac. The drive laser system sat directly above the microwave gun on the shielding blocks which formed the roof of the accelerator vault. This minimized the length of the optical transport system needed to deliver the light pulses to the cathode and allowed access to the drive laser during operation of the acceler-

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So by 1989, we could claim that we had successfully replicated in the Laboratory a basic physical mechanism that had last been operational in the Universe 13.6 billion years ago - and demonstrated a new laser technology in the process

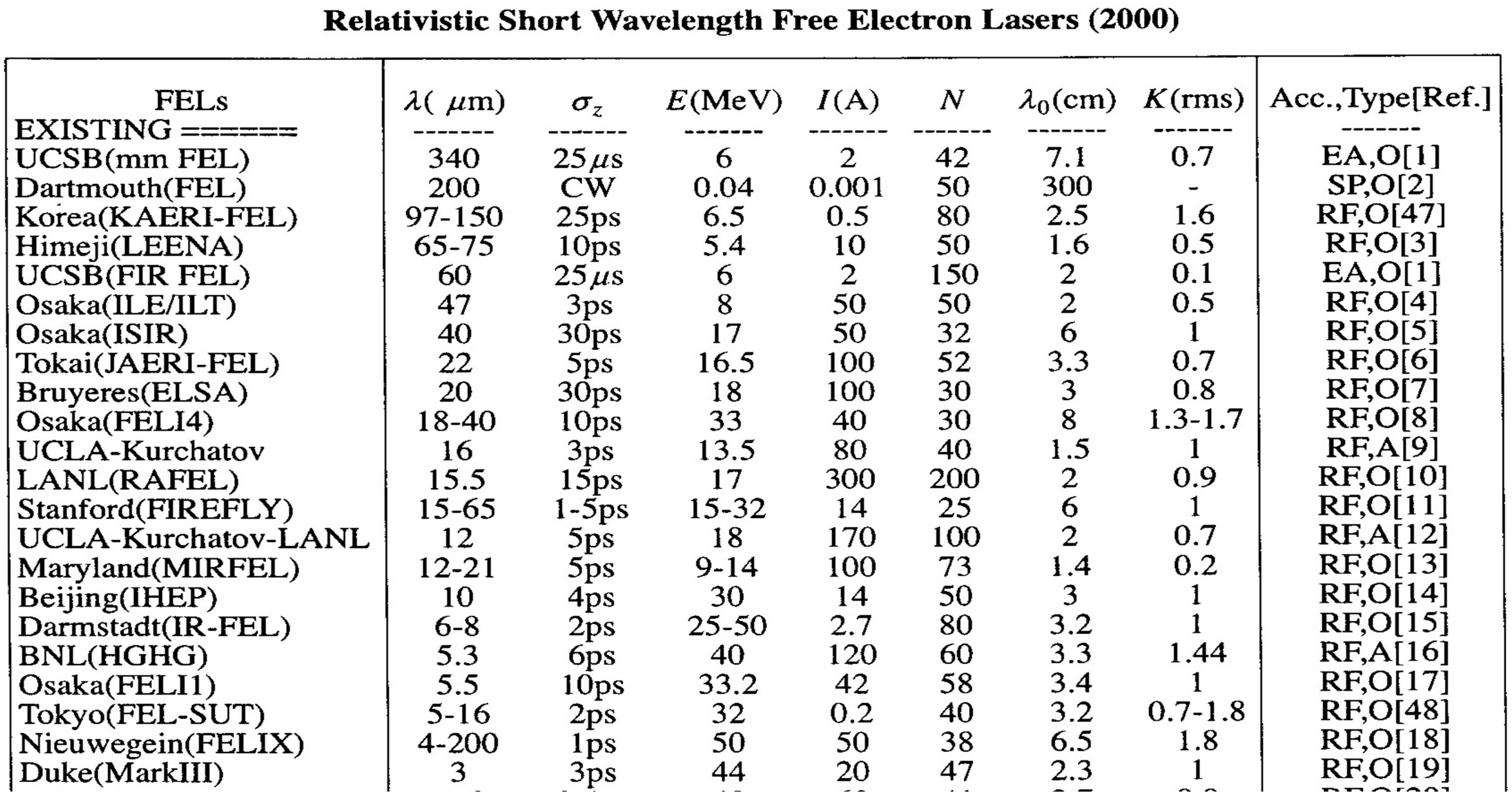
Implications of First Experiments

- Successful free-electron based light sources can be developed along the the lines described by Einstein, Schawlow and Townes based solely on transition rates
- The confinement of the emitted Compton photons to the forward 1/gamma cone resolved the fundamental limits to the operation of atomic and molecular lasers at x-ray wavelengths described by Schawlow and Townes
- The gain lineshape revealed by the amplifier experiments implied the existence of refractive guiding enhancing the prospects for high gain FEL systems
- The demonstration of effective high peak current, low emittance microwave electron guns established this approach as a candidate for the production of the even higher currents required for x-ray FELs

Re-Emergence of Role of Phase in the Limit of Strong Signals

- The analysis of strong field FEL operation re-established the key role of electron phase space dynamics (Bill Colson)
- The resultant analysis of the electrons’ phase space dynamics reveal several additional strong-field amplification modes
- Emergence of unexpected power and phase-related applications
- Phase selective amplification and emission proved effective in generation of squeezed state light

Experimental Demonstration of Laser Operation + Strong Signal Theory Generate Widespread Interest



Relativistic Short Wavelength Free Electron Lasers (2000)

FELs EXISTING ======	λ(μm) -------	σ_z -------	E(MeV) -------	I(A) -------	N -------	λ_0(cm) -------	K(rms) -------	Acc.,Type[Ref.] -------
UCSB(mm FEL)	340	25μs	6	2	42	7.1	0.7	EA,O[1]
Dartmouth(FEL)	200	CW	0.04	0.001	50	300	-	SP,O[2]
Korea(KAERI-FEL)	97-150	25ps	6.5	0.5	80	2.5	1.6	RF,O[47]
Himeji(LEENA)	65-75	10ps	5.4	10	50	1.6	0.5	RF,O[3]
UCSB(FIR FEL)	60	25μs	6	2	150	2	0.1	EA,O[1]
Osaka(ILE/ILT)	47	3ps	8	50	50	2	0.5	RF,O[4]
Osaka(ISIR)	40	30ps	17	50	32	6	1	RF,O[5]
Tokai(JAERI-FEL)	22	5ps	16.5	100	52	3.3	0.7	RF,O[6]
Bruyeres(ELSA)	20	30ps	18	100	30	3	0.8	RF,O[7]
Osaka(FELI4)	18-40	10ps	33	40	30	8	1.3-1.7	RF,O[8]
UCLA-Kurchatov	16	3ps	13.5	80	40	1.5	1	RF,A[9]
LANL(RAFEL)	15.5	15ps	17	300	200	2	0.9	RF,O[10]
Stanford(FIREFLY)	15-65	1-5ps	15-32	14	25	6	1	RF,O[11]
UCLA-Kurchatov-LANL	12	5ps	18	170	100	2	0.7	RF,A[12]
Maryland(MIRFEL)	12-21	5ps	9-14	100	73	1.4	0.2	RF,O[13]
Beijing(IHEP)	10	4ps	30	14	50	3	1	RF,O[14]
Darmstadt(IR-FEL)	6-8	2ps	25-50	2.7	80	3.2	1	RF,O[15]
BNL(HGHG)	5.3	6ps	40	120	60	3.3	1.44	RF,A[16]
Osaka(FELI1)	5.5	10ps	33.2	42	58	3.4	1	RF,O[17]
Tokyo(FEL-SUT)	5-16	2ps	32	0.2	40	3.2	0.7-1.8	RF,O[48]
Nieuwegein(FELIX)	4-200	1ps	50	50	38	6.5	1.8	RF,O[18]
Duke(MarkIII)	3	3ps	44	20	47	2.3	1	RF,O[19]

(Plus fifteen more)

For us, the Concept of Phase Also Lead to Several Other Kinds of Interactions

- Phase-independent amplification via the “phase displacement” principle
- Amplitude squeezing via phase-selective interactions with the quantum zero-point fluctuations
- Role of boundary conditions in attaining near-perfect phase coherence and the first indications of the presence of advanced interactions

Phase Displacement Principle Yields Phase-Independent Amplification !!

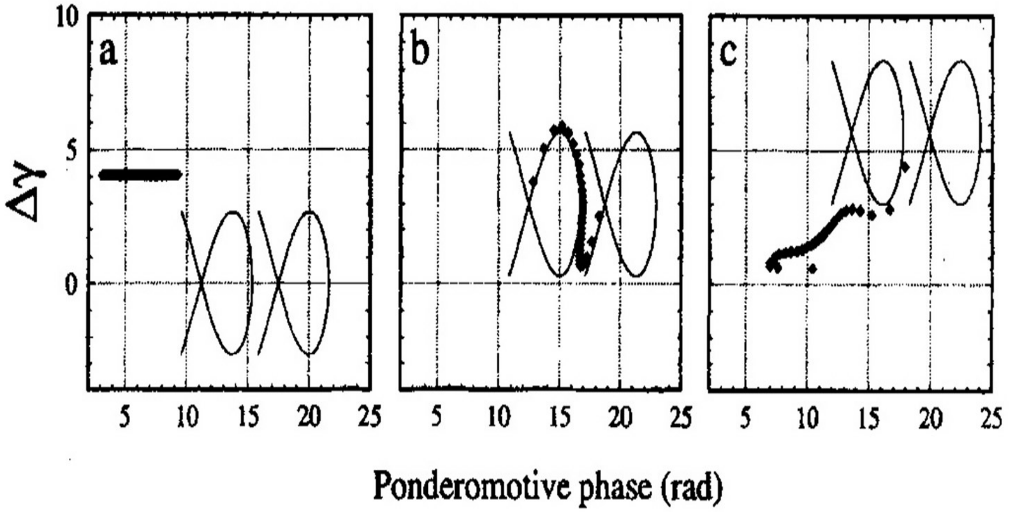


Fig. 6. Phase-space distributions at: (a) the beginning; (b) the middle; and (c) the end of the wiggler for the inverse-tapered FEL at saturation (bunch charge $Q_b = 75$ pC; taper $= -36.51$). Separatrices are shown as solid lines. Note the reduced energy spread in (c).

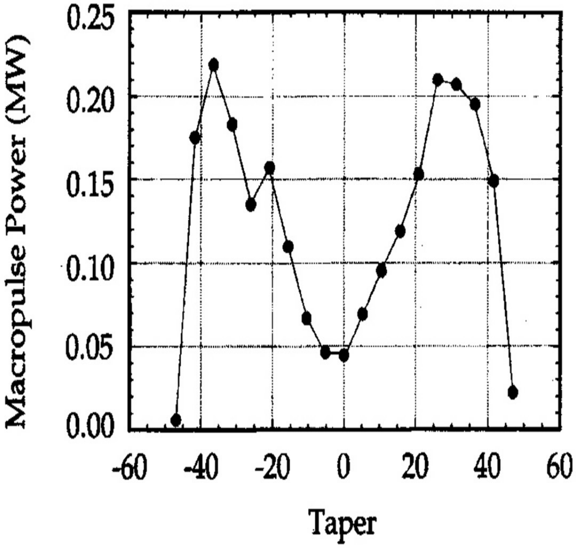
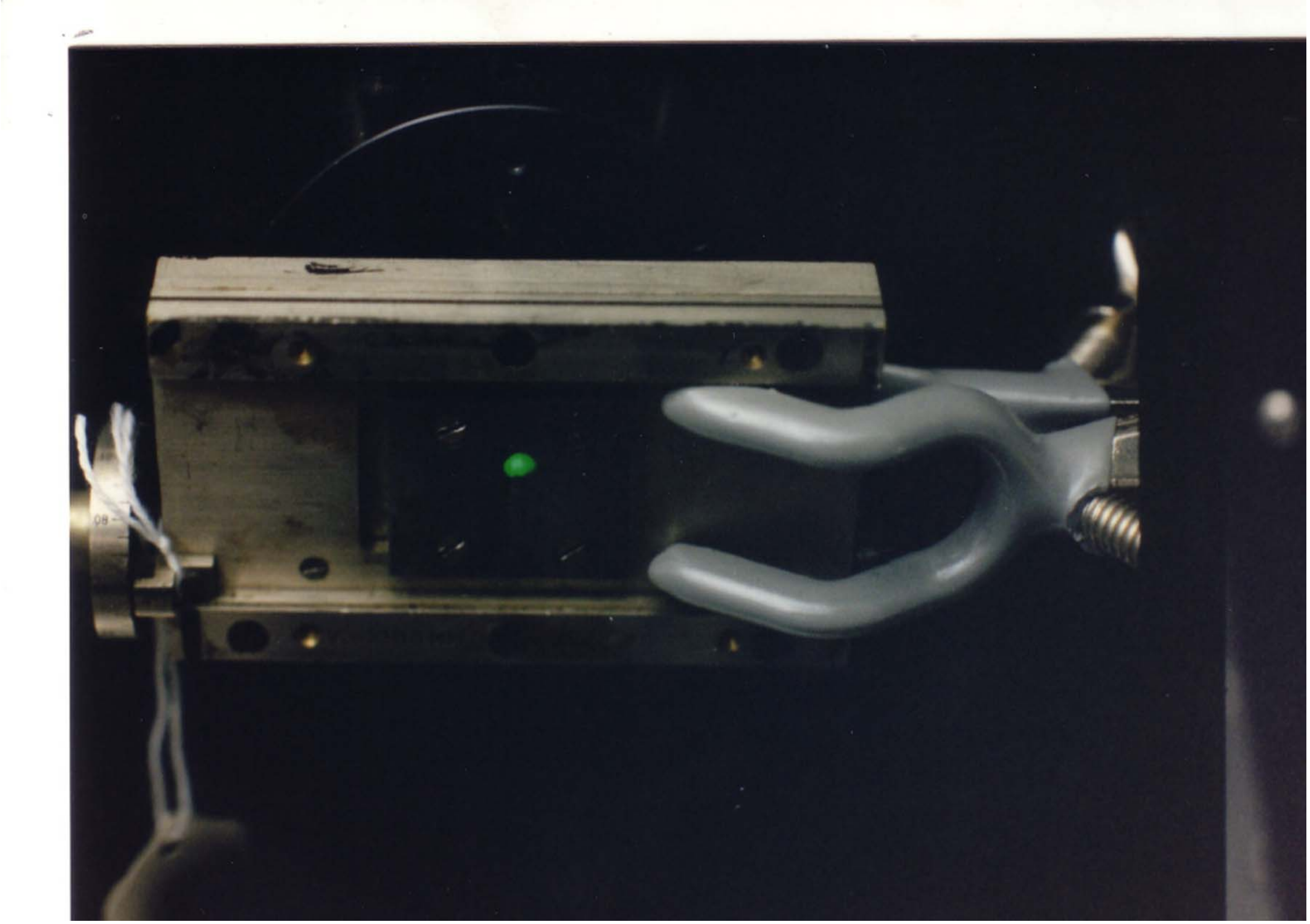


Fig. 5. Macropulse power at saturation for various tapers ($Q_b = 75$ pC).

Key Role of Phase in Amplitude Squeezing of Coherent Harmonics



Measured Intensity Fluctuations are sub-Poisson

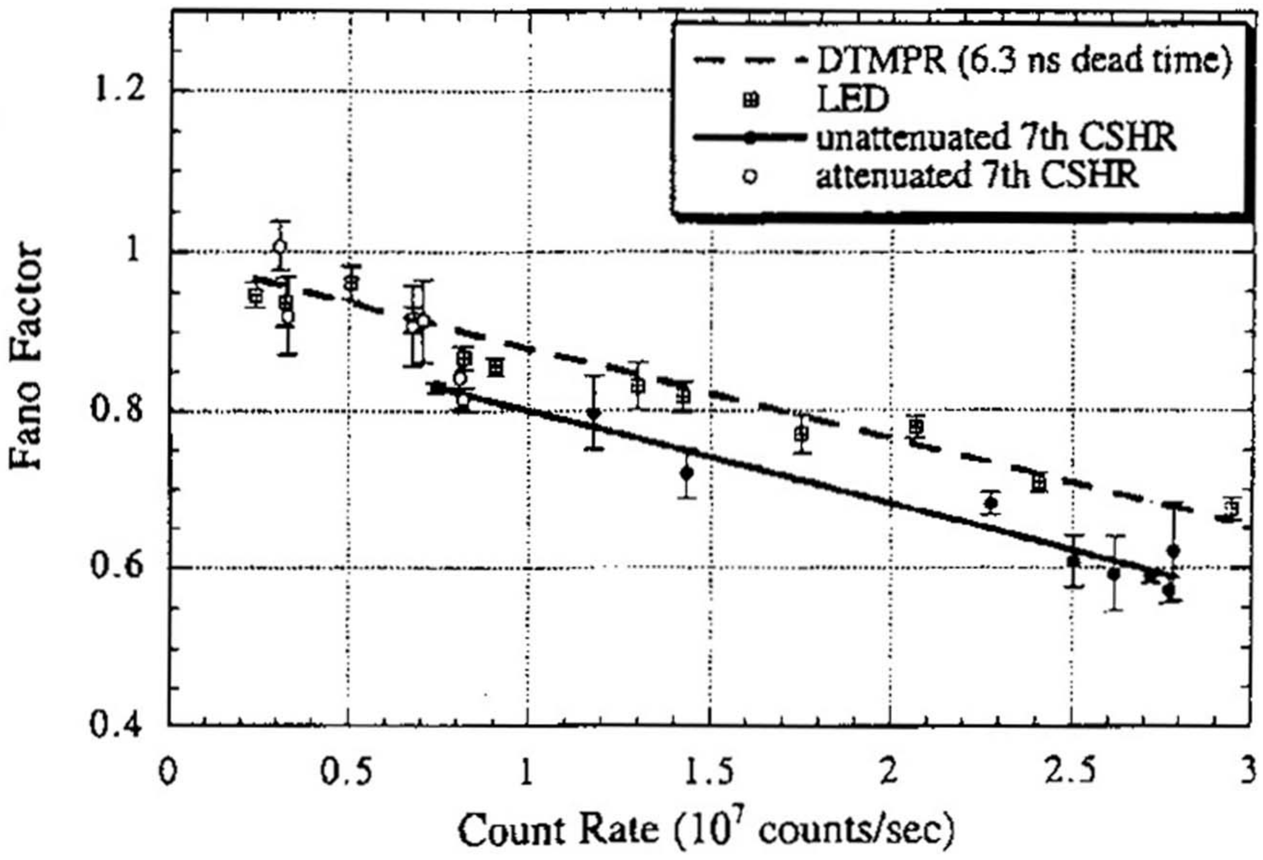
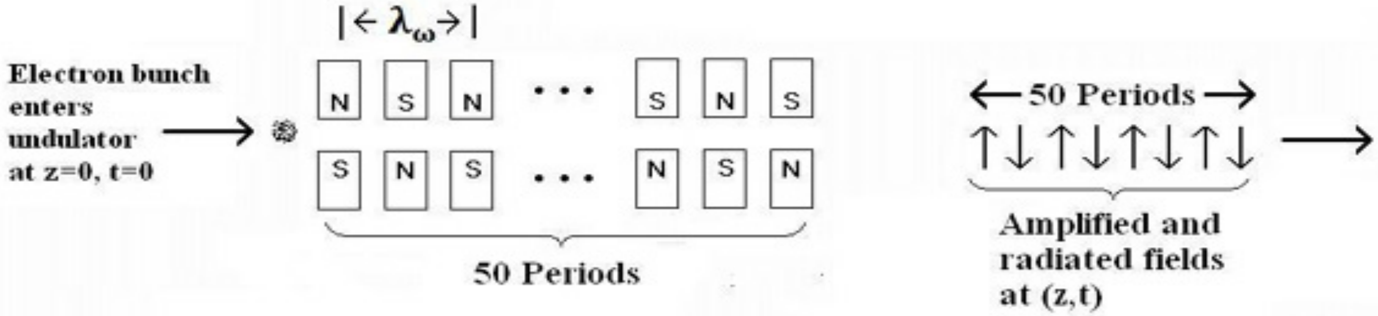


FIG. 2. Reduction of the Fano factor for seventh CSHR (solid line) compared to the theoretical DTMPR (dashed line) and an experimental Poisson source (LED). The error bars indicate the measured standard deviation of the experimental data points.

Tightly Bunched Beams Emit and Amplify Harmonic Radiation in Quadrature



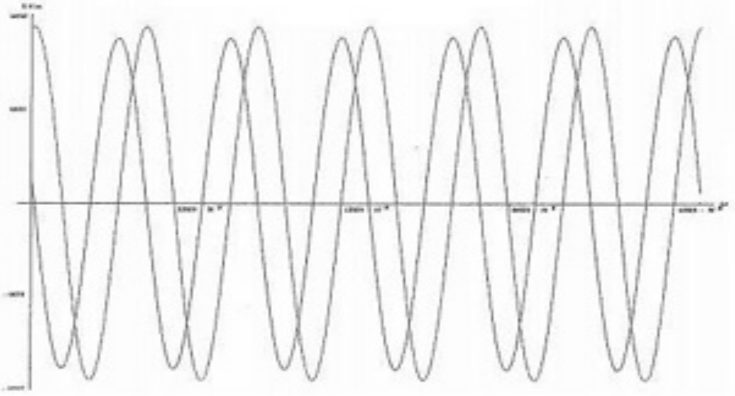
Electron bunch enters undulator at z=0, t=0 ⟶

50 Periods

Amplified and radiated fields at (z,t)

$$\overrightarrow{E_1}(z,t) = \vec{E}_{\text{radiated}}(z,t) = \frac{ne^2B_0\gamma}{\pi\varepsilon_0 cm}\frac{1}{z+2\gamma^2(z-ct)}\sin\left[\frac{4\pi\gamma^2}{\lambda_\omega}c\left(t-\frac{z}{c}\right)+\pi\right]\hat{x},\ \left(\frac{z}{c}\le t\le\frac{50\lambda_\omega}{\gamma^2 c}+\frac{z}{c}\right)$$

$$\overrightarrow{E_2}(z,t) = \vec{E}_{\text{amplified}}(z,t) = E_0\cos\left[\frac{4\pi\gamma^2}{\lambda_\omega}c\left(t-\frac{z}{c}\right)\right]\hat{x} = E_0\sin\left[\frac{4\pi\gamma^2}{\lambda_\omega}c\left(t-\frac{z}{c}\right)+\frac{\pi}{2}\right]\hat{x}$$



Phase difference between these two E fields is $\frac{\pi}{2}$

Amplitude Squeezing is a Strong Signal Effect

Amplification of the randomly fluctuating “zero point noise sidebands” responsible for phase fluctuations reduces the amplitude of the sidebands responsible for amplitude fluctuations generating an “amplitude squeezed state”

from Caves, Braginsky and Thorne, etc

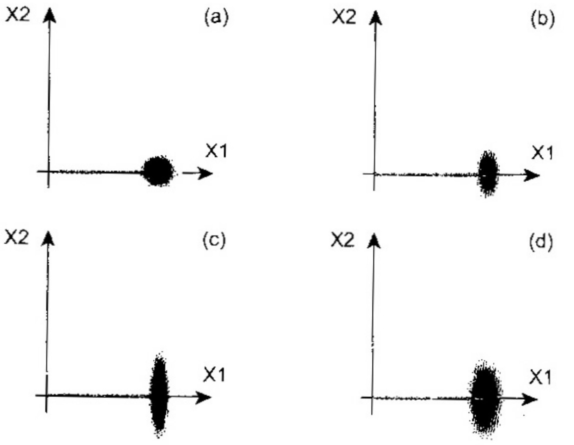


Figure 9.6: Phasor diagram comparing squeezed and other states: (a) Coherent state, (b) Minimum uncertainty squeezed state which is narrower than the coherent state in one direction, (c) Squeezed state with excess noise, (d) An asymmetric, noisy but not squeezed state – it is described by an ellipse, but no projection is narrower than the coherent state.

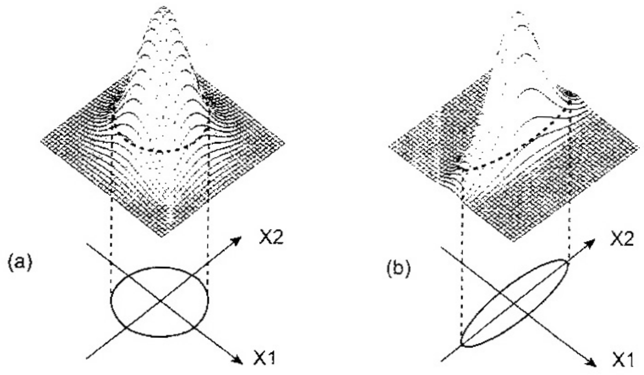
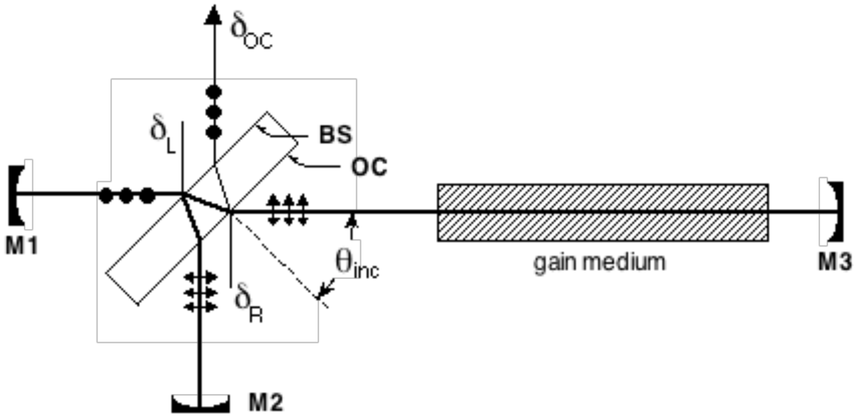
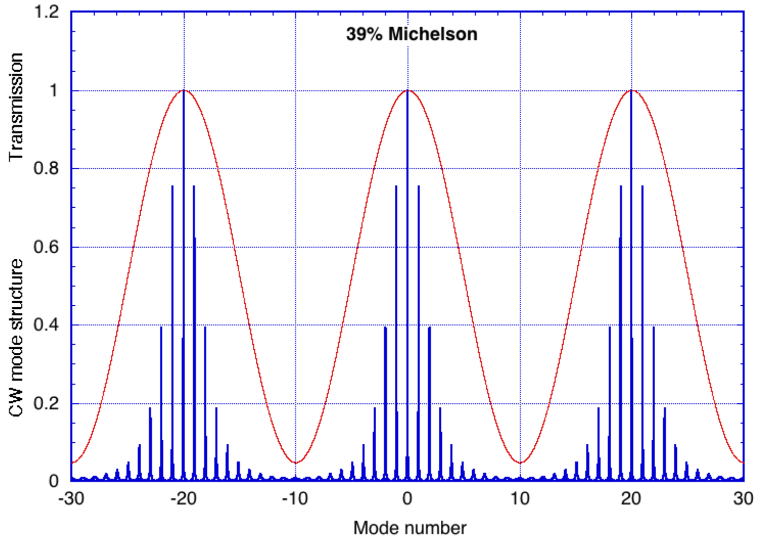


Figure 9.7: Wigner function of (a) coherent state and (b) squeezed state

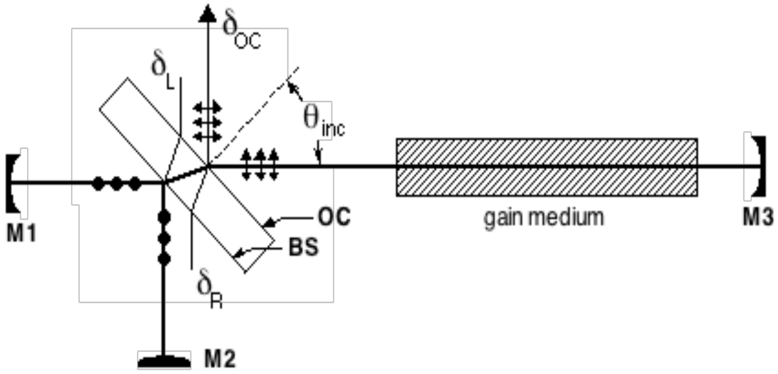
Near-Absolute Phase Coherence Attainable by Modification of Boundary Conditions, but by What Mechanism ??

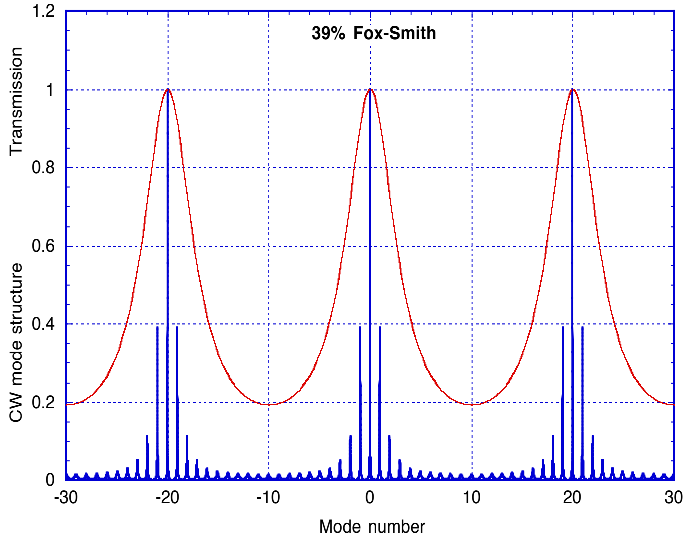
Michelson Interferometer





Fox-Smith Interferometer

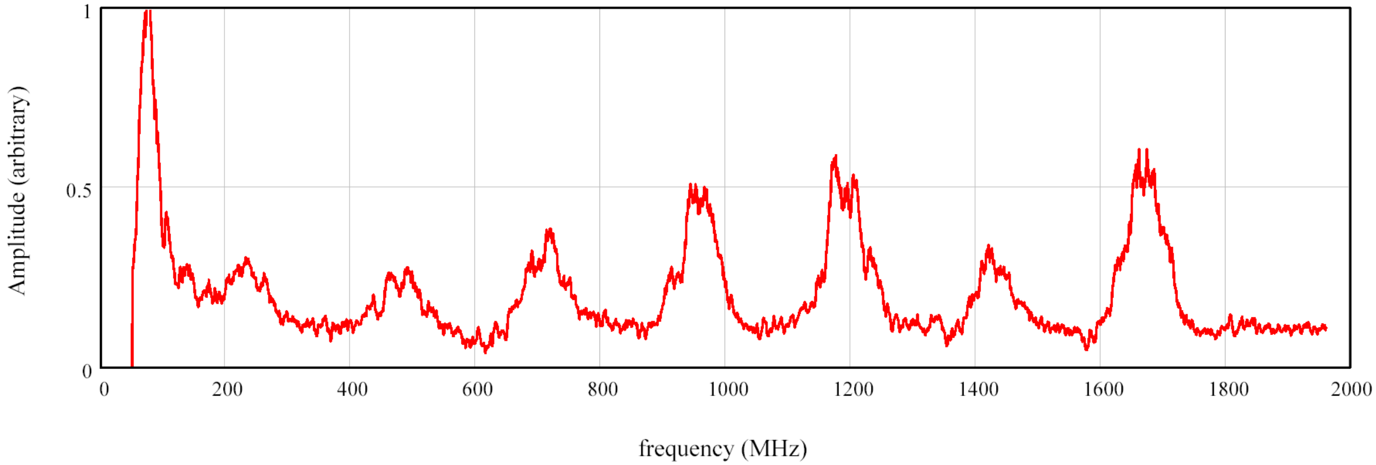




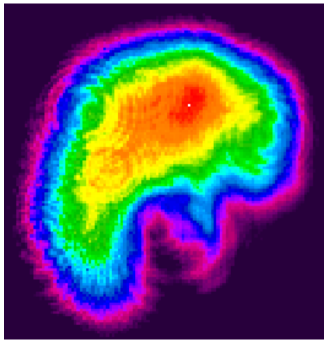
Reference: Eric B. Szarmes, "Birefringent beam splitter for intracavity mode selection in high-power multimirror lasers," *Appl. Optics, vol.* ***33****,* pp. 6953-6964, 1994.

Spectral and Spatial Mode Quality of the MKIII FEL

Measured Dye Laser Multi-Mode Spectrum

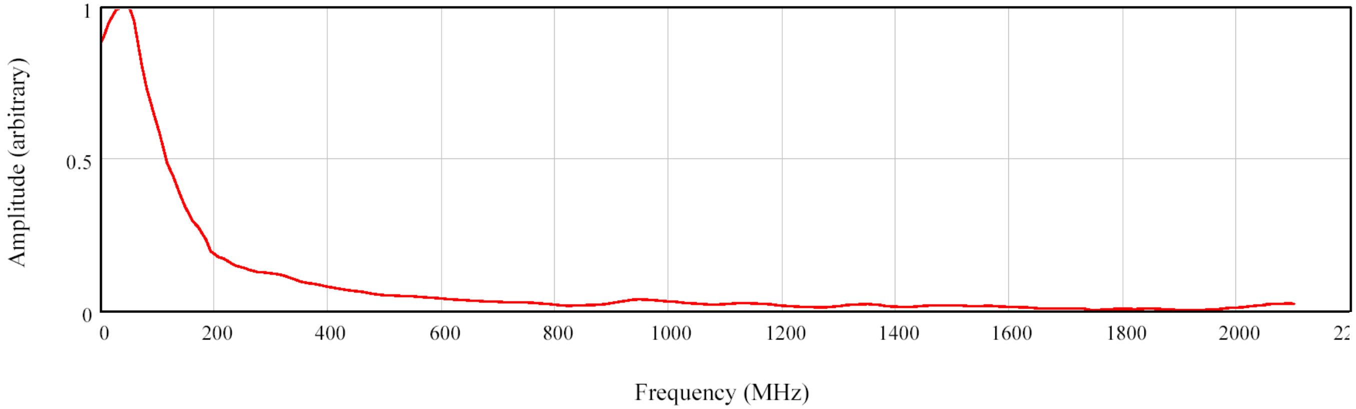


Distorted beam profile
(non-uniform color)

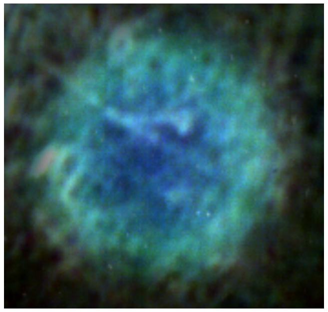


CCD Image

Measured FEL Single-Mode Spectrum



Symmetric beam profile
(uniform color)

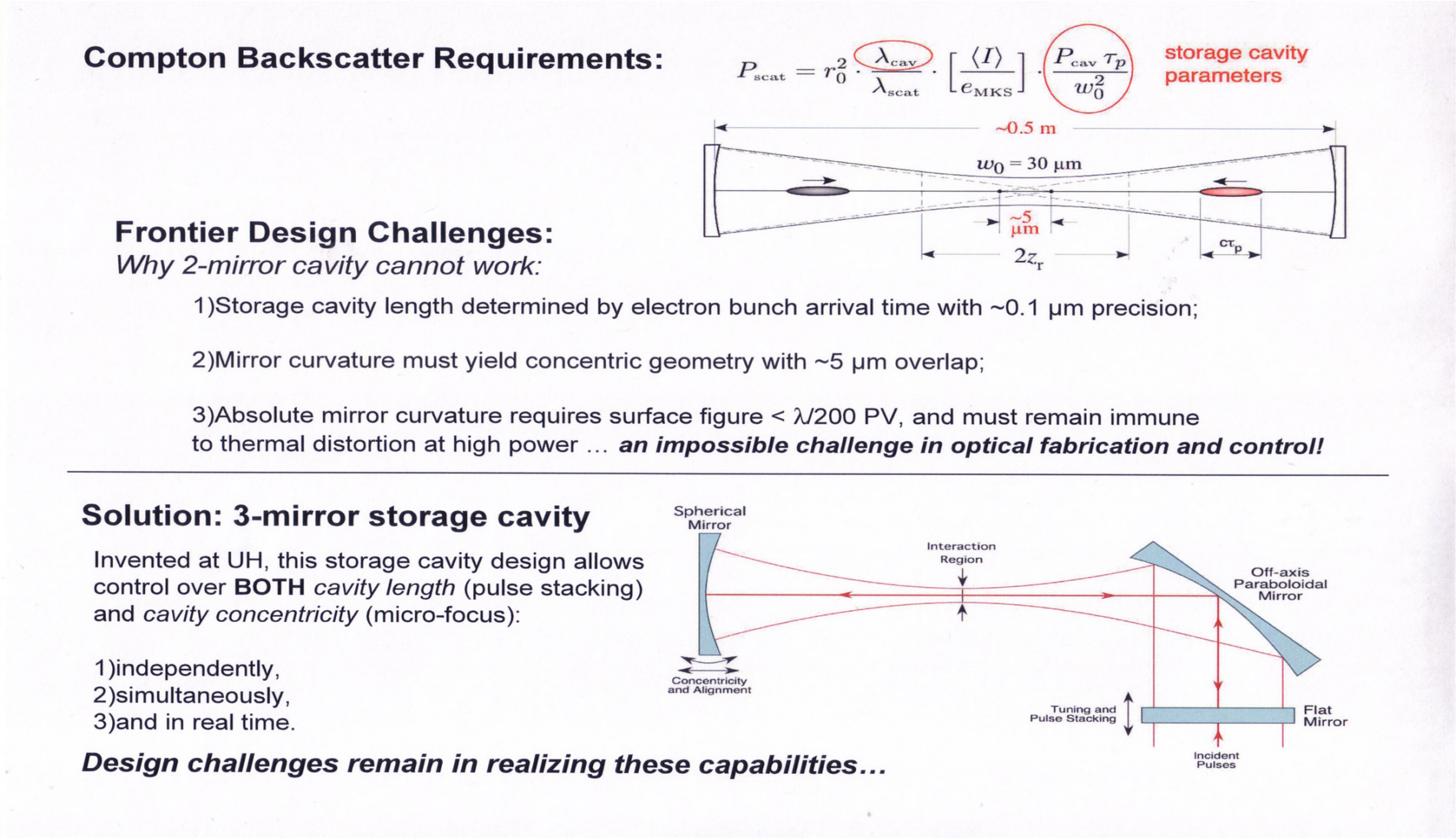


Thermal Image

Phase Coherent Optical Pulse Trains Create New Opportunities for High Field Research and Applications

- Phase coherent pulses can be efficiently stacked in optical storage cavities
- The stored pulses can be brought to a diffraction-limited microfocus through use of a near-confocal cavity geometry to achieve unprecedented, sustained optical power densities
- Estimates of the limits imposed by thermal distortion suggest that systems operating at stored optical energies of the order of 1 Joule can practically be realized

Phase Coherent Pulse Trains + Novel Cavity Designs Enable Storage of Unprecedented Peak Powers



Compton Backscatter Requirements:

$$P_{\text{scat}} = r_0^2 \cdot \frac{\lambda_{\text{cav}}}{\lambda_{\text{scat}}} \cdot \left[\frac{\langle I \rangle}{e_{\text{MKS}}}\right] \cdot \frac{P_{\text{cav}}\,\tau_p}{w_0^2}$$

storage cavity parameters

Frontier Design Challenges:

Why 2-mirror cavity cannot work:

1)Storage cavity length determined by electron bunch arrival time with ~0.1 μm precision;

2)Mirror curvature must yield concentric geometry with ~5 μm overlap;

3)Absolute mirror curvature requires surface figure < λ/200 PV, and must remain immune to thermal distortion at high power … ***an impossible challenge in optical fabrication and control!***

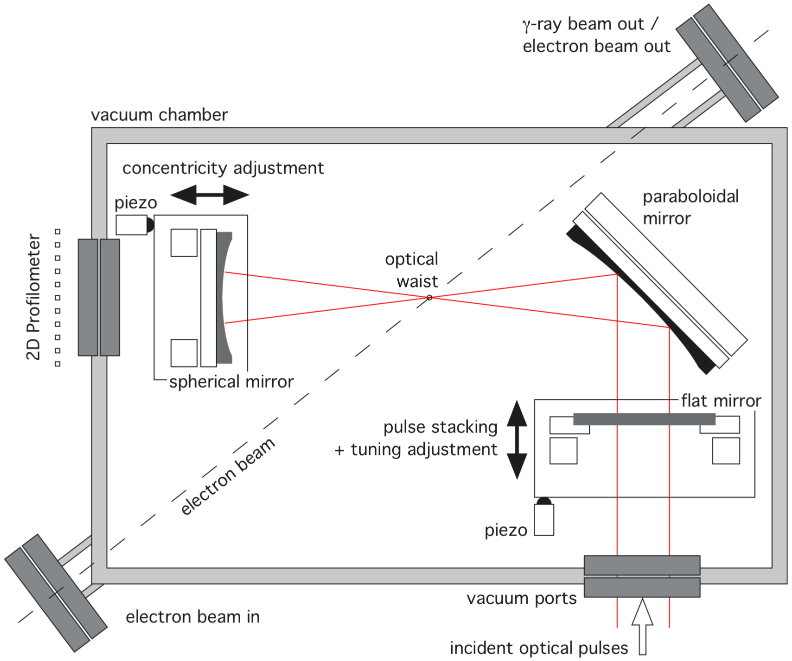
Solution: 3-mirror storage cavity

Invented at UH, this storage cavity design allows control over **BOTH** *cavity length* (pulse stacking) and *cavity concentricity* (micro-focus):

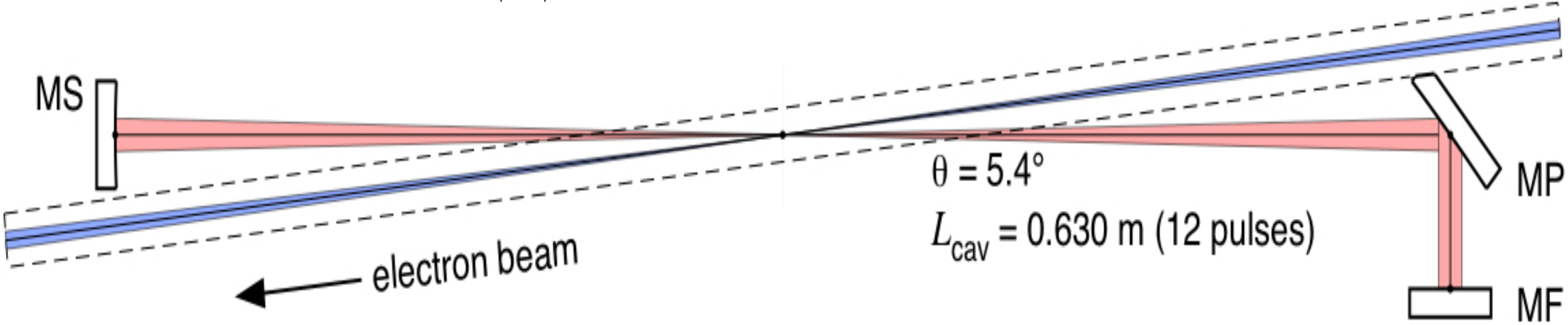
1)independently,
2)simultaneously,
3)and in real time.

Design challenges remain in realizing these capabilities…

“Optical Undulators” for Inverse-Compton X-Ray Sources



The ability to generate GHz rep rate circulating optical pulses with peak powers consistent with thermal loading at normalized vector potentials as large as 0.1 creates the opportunity for high average scattering rates IF the rep rate of the optical pulses can be matched by the rep rate of the counter-propagating electron bunches



Ultraviolet and X-Ray FEL Operation

- Schalow and Townes demonstrated in their paper that X-Ray lasers were probably impossible, but….
- Their arguments do not apply to lasing by lasing media moving at relativistic velocities, further
- The possibilities for guided mode propagation were suggested by the earliest experiments at Stanford, even if the required electron currents would still be a challenge
- The multiple analyses and experiments in the 20 years that followed the Stanford experiments established the full details of coupled mode propagation in high gain FELs
- The parallel refinement of microwave gun and ebeam transport systems have enabled the generation of the very high peak current, very high quality electron beams required for operation at X-ray wavelengths

Past as Prologue

- A critical review of the simple long-accepted physics of coherent emission has revealed a fundamental flaw in the long-accepted “retarded only” model of macroscopic classical electrodynamics
- The “retarded only” formulation of electrodynamics does not provide the fields needed to satisfy Maxwell’s equations !!

Recent Paper by Niknejadi Establishes:

- The electric fields acting on pairs of oscillating particles must vary with the particles' spacings as required to satisfy "Maxwell's energy integral"
- The fields calculated using Sommerfeld's "retarded only" formulation of electrodynamics do not pass this test
- The fields calculated using Wheeler and Feynman's time-symmetric formulation of electrodynamics exactly satisfy this test

Critical Re-Appraisal of the Foundations of Electrodynamics

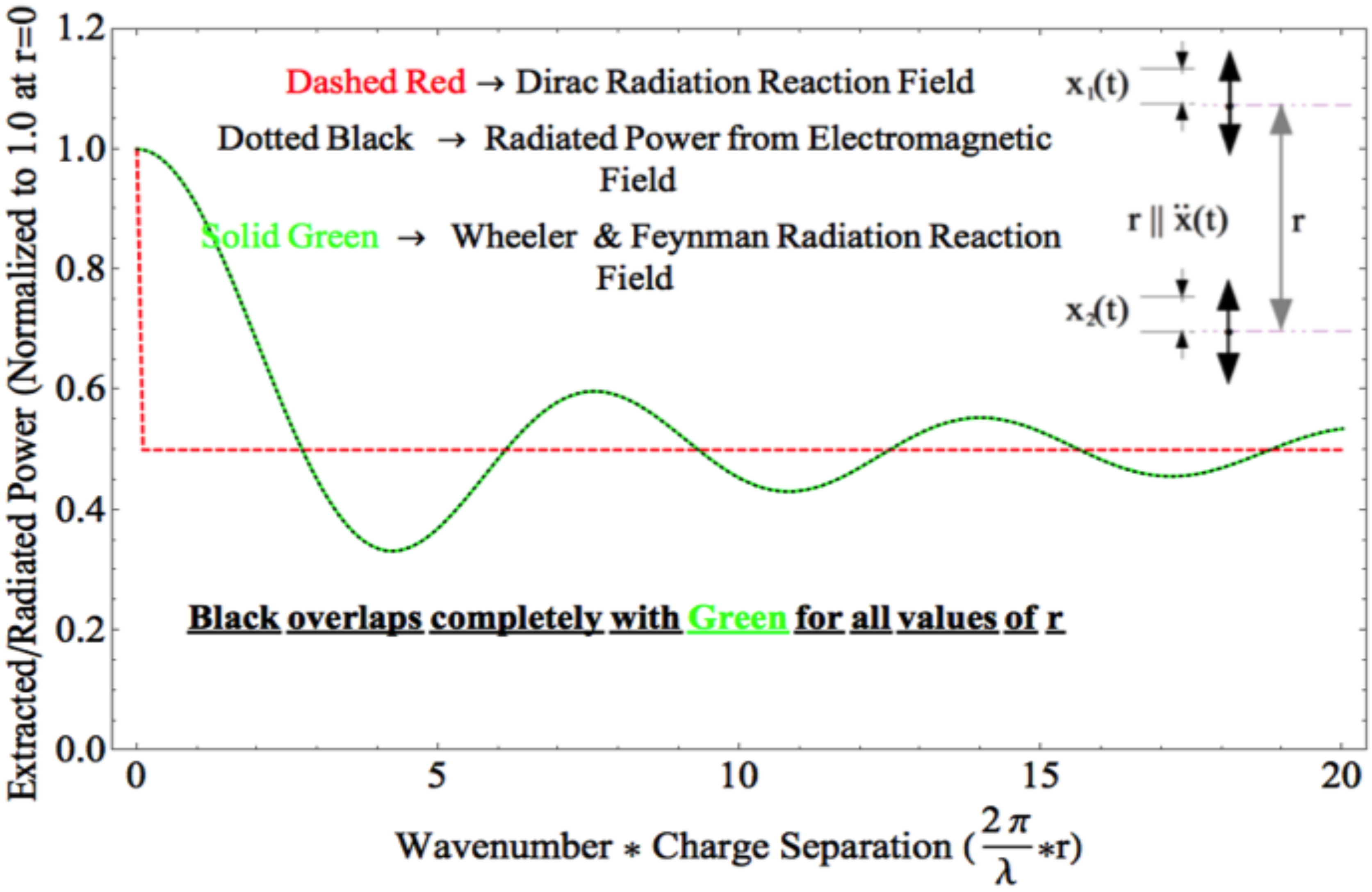
For periodically oscillating charges and currents:

$$-\int_A^B dt\,\frac{d}{dt}\int\left[\frac{E^2}{2}+\frac{H^2}{2}\right]dV = -\int_A^B dt\,\frac{d}{dt}\int\left[\left(\mathrm{E}\times\mathrm{H}\right)d\mathrm{a} + \int \mathrm{E}\bullet\mathrm{j}\,dV\right]$$

$$-\left\langle \frac{d}{dt}\int\left[\frac{E^2}{2}+\frac{H^2}{2}\right]dV\right\rangle = 0$$

$$\Rightarrow \left\langle \int\left(\mathrm{E}\times\mathrm{H}\right)d\mathrm{a}\right\rangle = -\left\langle \int \mathrm{E}\bullet\mathrm{j}\,dV\right\rangle$$

Sommerfeld's Retarded Fields Fail Niknejadi's Test !



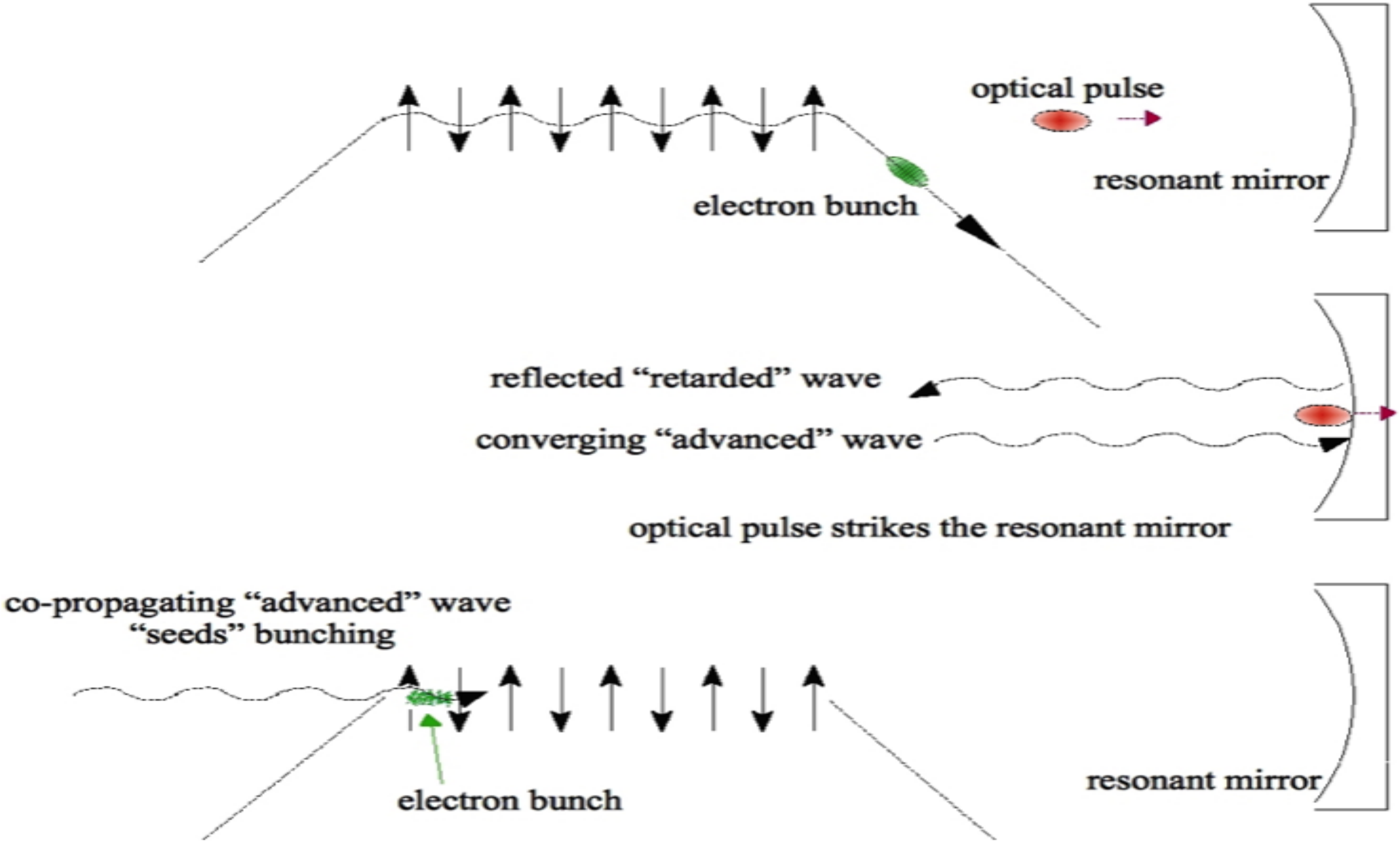
What could this mean (1) ?

- Maybe no surprise: Wheeler and Feynman’s time symmetry has long been assumed to govern the interaction of elementary particles at the micro scale, so why not the macro scale ??
- Niknejadi’s test should apply equally at the micro scale of elementary particle interactions and the macro scale of optical and radio wavelengths
- According to Niknejadi et al, the advanced fields of interacting currents should thus be measurable in the near-field regions of these currents including radio and microwave antennas

What could this mean (2) ?

- The advanced fields attributable to interacting charges and currents could significantly clarify our understanding of the interactions of radiating charges and their environment
- As pointed out by Niknejadi, designers of new FEL light sources could have a new means available to optimize coherence of the source by optimizing the spectral dispersion of the target

Possible Use of "Resonant Mirrors" to Enhance the Coherence of SASE FELs



What could this mean (4)?

- If validated by experiment, the interactions attributable to time symmetry could be seen as the manifestation of Mach’s principle in electrodynamics on the cosmic, as well as the laboratory scale
- The advanced interactions implicit in Schroedinger’s equation have also been identified by Cramer as providing an alternate and objective explanation of the experiments demonstrating “backwards causation” and entanglement in quantum mechanics

Conclusions: Learning about Learning

- Revising Feynman's dictum "You can't learn anything unless you know it already" (only works for classroom instruction, not for discovery)
- Curiosity and preparation are key
- Seemingly adverse circumstances can stimulate the intellectual and practical aspects of innovation
- While learning is incremental, each step into the unknown can have far-reaching consequences
- Theories may be the precursor of all of our concepts, but only an experiment can validate our understanding of physical reality
- We have in our time only scratched the surface of what remains to be learned about the Universe

References

A comprehensive compilation of the references for the developments referenced in this talk can be found in my paper "From Vacuum Tubes to Lasers and Back Again" in Phys. Rev ST Accelerators and Beams **17**, 074901 (2014)

The more recent discussions of the failures of Sommerfeld's "retarded only" formulation of electrodynamics appear in Niknejadi's paper "Radiated Power and Radiation Reaction Forces of Coherently Oscillating Charged Particles in Classical Electrodynamics" in Phys. Rev. D 91 096006 (2015)